NON-{$D\bar{D}$ DECAYS OF THE $\Upsilon^*$ (3770)

BY

WALID ABDUL MAJID

B.A., Swarthmore College, 1986
M.S., University of Illinois at Urbana-Champaign, 1988

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Physics
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1993

Urbana, Illinois
WE HEREBY RECOMMEND THAT THE THESIS BY

WALID ABDUL MAJID

ENTITLED NON-DD DECAYS OF THE \( \eta' \) (3770)

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF DOCTOR OF PHILOSOPHY

[Signatures]

Director of Thesis Research
Head of Department

Committee on Final Examination†

[Signatures]
Chairperson

† Required for doctor's degree but not for master's.
NON-$D\bar{D}$ DECAYS OF THE $\Psi''$ (3770)

Walid Abdul Majid, Ph.D.
Department of Physics
University of Illinois at Urbana-Champaign, 1993
Jon J. Thaler, Advisor

A search for inclusive non-$D\bar{D}$ decays of the $\Psi''(3770)$ is performed in a sample of $9.56\pm0.48$ pb$^{-1}$ collected by the Mark III detector at the SPEAR storage ring, at the Stanford Linear Accelerator Center. To be more specific, a search for inclusive $\bar{p}, \bar{\Lambda}$, and $\phi$ decay modes of the $\Psi''(3770)$ is performed in this data sample. Backgrounds due to the decays of the radiatively produced $\Psi'(3686)$ are subtracted. Also backgrounds due to the production of the same final state by nonresonant $e^+e^-$ annihilation are subtracted. After further background subtractions from $D$ meson decays and particle misidentification and efficiency corrections no events are seen and upper limits are placed for each one of these decay channels.
Acknowledgements

Thanking everyone who has helped me during my graduate studies is truly a difficult task. I therefore ask forgiveness from those whom I have overlooked in these acknowledgements.

First I want to thank my thesis advisor Jon Thaler for his guidance and encouragements throughout my career as a graduate student. I am very grateful for his patience and his support in helping me broaden my knowledge in physics. I want to also thank Gary Gladding and Rafe Schindler for teaching me many things about physics analyses. I have very much enjoyed working with Gary and Rafe in the vertexing group of SLD. I will always be grateful for their guidance in the analyses for this thesis.

Since I worked on the SLD experiment before working on the Mark III analysis, I want to thank many on SLD specially Bob Eisenstein, Inga Karliner, Joe Izen, John Megowan, Richard Dubois, J. J. Russel, Mike Hufer, Iris Abt, Tony Johnson, Jon Labs, and Tom Junk.

I want to also thank Ramon Berger, Tom Shaw and Kazuko Onaga for making my graduate school years easier.

I would like to thank my grandparents for starting my education by teaching me how to read and write and encouraging me to excel in my studies in Afghanistan. I would also like to thank my aunt for her constant attention towards my studies.

I especially want to thank my wife Homaira, who has given my life a new meaning. I thank her for all she had to put up with during the writing days and nights of this thesis.

Most significantly I want to thank my parents Kamar and Abdul Majid for everything they have given up for me, and everything they have provided for me. It has been with their
support and love that I have been able to pursue my education in physics. I would like to dedicate this thesis to them.

This research was supported in part by the U.S. Department of Energy, under contract DE-AC02-76ER01195 and contract DE-AC02-76ER40677.
# Table of Contents

Chapter 1  Motivation................................................................................. 1
  1.1  Overview ....................................................................................... 1
  1.2  The Charmonium Model ............................................................... 5
    1.2.1  Spectroscopy ....................................................................... 5
    1.2.2  $^3S_1 - D_1$  Mixing ............................................................. 7
    1.2.3  Transition Rates ................................................................... 8
  1.3  The Okubo - Zweig - Iizuka Rule .................................................. 11
  1.4  Scaling .......................................................................................... 14

Chapter 2  The Mark III Experiment and Data Processing 16
  2.1  Introduction .................................................................................. 16
  2.2  The Drift Chambers .................................................................... 19
  2.3  The Time of Flight System ............................................................ 23
  2.4  The Shower Counters .................................................................. 26
  2.5  The Magnet .................................................................................. 28
  2.6  The Muon System ........................................................................ 28
  2.7  The Event Trigger ........................................................................ 29
  2.8  The Data Samples ........................................................................ 31
  2.9  Monte Carlo Event Generators ...................................................... 31
  2.10  The Filter ..................................................................................... 32
  2.11  Drift Chamber Reconstruction .................................................... 33
  2.12  Time of Flight Reconstruction .................................................... 35
  2.13  Shower Counter Reconstruction .................................................. 36
  2.14  The Muon Detector Reconstruction .............................................. 38
Chapter 3  \( \Psi(3686) \) Normalization .............................................. 39

3.1 Introduction ...........................................................................39
3.2 Event Selection .........................................................................40
3.3 Particle Id ................................................................................41
   3.3.1 Using the Muon System ....................................................41
   3.3.2 Using the E/P Method .......................................................42
3.4 Kinematic Fits to the Desired Final State ...............................42
3.5 Detection Efficiency ...............................................................47
3.6 Determining the Number of \( \Psi(3686) \) .................................54
3.7 Results ...................................................................................61

Chapter 4  Four Pion Production .................................................62

4.1 Introduction .............................................................................62
4.2 General Event Selection ..........................................................63
4.3 Particle Identification ...............................................................63
4.4 Event Momentum, Energy, and Kinematic Fits to \( \pi^+\pi^-\pi^+\pi^- \) ...64
4.5 \( \Psi\pi^+\pi^- \) Background .........................................................68
   4.5.1 Using the Radiative \( \Psi \) Production Monte Carlo ..........72
   4.5.2 Searching for \( \gamma\Psi\pi\pi \) events among the \( \pi^+\pi^-\pi^+\pi^- \) candidates ...72
4.6 Results ...................................................................................75

Chapter 5  Inclusive Anti-proton Production ................................76

5.1 Introduction .............................................................................76
5.2 Event and Track Selection .......................................................76
5.3 Proton Reconstruction .............................................................78
5.4 Proton Identification ...............................................................78
5.5 Calculating the Number of Protons from \( \Psi^* \) Decays ..........85
5.6 Proton Detection Efficiencies ..................................................87
   5.6.1 Efficiency Ratios at the Two Energies ..............................87
5.7 Backgrounds ..........................................................................89
   5.7.1 Decays of the \( \Psi(3686) \) ..................................................89
   5.7.2 Decays of D Mesons .......................................................92
5.7.3 Misidentified Tracks ............................................... 92
5.7.4 Continuum Production ............................................ 97
5.8 Results ........................................................................ 98
  5.8.1 The Scaling Variables ............................................. 99
  5.8.2 Comparison With the Lund Monte Carlo .................. 102
  5.8.3 Determining the Branching Fraction ......................... 102

Chapter 6 Inclusive Λ Production ......................... 104
  6.1 Introduction .......................................................... 104
  6.2 Ā Reconstruction ................................................... 104
    6.2.1 Event and Track Selection .................................. 104
    6.2.2 Proton and Pion Track Reconstruction .................. 105
  6.3 Proton Identification ............................................. 115
  6.4 Ā Reconstruction ................................................... 115
  6.5 Calculating the Number of Λ’s from Ψ'' Decays ............. 118
  6.6 Overall Λ Detection Efficiency ............................... 120
    6.6.1 Efficiency Ratios at the Two Center of Mass Energies .. 123
  6.7 Determining the Number of Λ’s ................................. 123
  6.8 Results ............................................................... 127
    6.8.1 The Scaling Variables ........................................ 129
    6.8.2 Comparison With the Lund Monte Carlo ................ 132
    6.8.3 Determining the Branching Fraction ....................... 133

Chapter 7 Inclusive φ Production ...................... 134
  7.1 Introduction .......................................................... 134
  7.2 Event and Track Selection ....................................... 134
  7.3 Reconstructing φ daughter tracks ............................ 136
  7.4 Kaon Identification ............................................... 140
  7.5 φ Reconstruction ................................................... 142
  7.6 Calculating the Number of φ’s from Ψ'' Decays ............ 142
  7.7 Overall φ Detection Efficiency ............................... 145
    7.7.1 Efficiency Ratios at the Two Center of Mass Energies .. 148
  7.8 Determining the Number of φ’s ................................. 148
  7.9 φ’s From Decays of D Mesons ................................. 151
Chapter 1

Motivation

1.1 Overview

In November of 1974, the discovery of an extremely narrow resonance, now known as the \( J/\psi \), opened up a new chapter in the field of high energy physics. The \( J/\psi \) was simultaneously discovered in two very different experiments, in \( e^+e^- \) collisions at SPEAR, an \( e^+e^- \) storage ring at Stanford Linear Accelerator Center, as well as in proton beryllium collisions at the Brookhaven AGS.[1] [2]

The \( J/\psi \), which will be referred to as the \( \psi \), is assigned the quantum numbers \( J^{PC} = 1^- \), the same as those of the photon, \( \rho \), \( \omega \), and \( \phi \). This assignment is justified by the dispersion-like shape of the resonance in \( e^+e^- \) collisions, which is characteristic of two interfering amplitudes: the direct channel, as well as the virtual photon mediated production of the \( \psi \). The high mass of the \( \psi \) (3097 MeV/c\(^2\)) and its low spin suggest a low lying state of heavy quarks interpretation rather than a high lying state of light quarks. The \( \psi(3097) \), and the \( \psi(3686) \) (also called \( \psi' \)) discovered a week later at SPEAR, is interpreted as bound states of quark and anti-quark, each carrying a new quantum number “charm”. [3] The most remarkable feature of the \( \psi \) and \( \psi' \), however, is their extremely narrow width (86 keV and 278 keV respectively), about \( 10^3 \text{–} 10^4 \) times smaller than naive expectations for a hadronic state of such high mass. [4] This extreme narrowness or long lifetime is indicative of highly suppressed decays to ordinary hadrons, wherein the new quantum number is believed to be lost.

The existence of charm was predicted long before its discovery, by Glashow, Iliopoulos and Maiani in 1970 when they were trying to explain the suppression of strangeness changing neutral currents and the suppression of certain second order weak processes such as \( K_L^0 \to \mu^+\mu^- \) and \( K^+ \to \pi^+\nu\bar{\nu} \).[5] In fact the mass of the charmed (c) quark was pre-
dicted by Gaillard and Lee to be in the region of 1-2 GeV by calculating the rate for the process \( K_L^0 \rightarrow \mu^+ \mu^- \).\[^6\]

Soon after the discovery of the \( \Psi \) and the \( \Psi' \), another charmonium resonance with a mass of 3770 MeV/c\(^2\) was discovered at SPEAR.\[^7\] This new charmonium state which was named \( \Psi''(3770) \) or just \( \Psi'' \) is expected to have the photon quantum numbers \( J^{PC} = 1^{--} \), since it couples to \( e^+e^- \). The \( \Psi''(3770) \) is interpreted within the standard charmonium model as the \( 1^3D_1 \) state, mixed with the \( 2^3S_1 \) state to give a relatively large decay width to \( e^+e^- \).\[^8\] The total width of the \( \Psi''(3770) \) is 23.6 MeV, which is about 100 times larger than that of \( \Psi(3686) \), even though their mass difference is only 84 MeV/c\(^2\).\[^4\] The large width of the \( \Psi''(3770) \) can be explained by the fact that the \( \Psi''(3770) \) mass is above \( 2m_D \) (the factor of two is here because the charm quantum number is conserved by the strong interaction), opening the Okubo-Zweig-Iizuka (discussed later in Section 1.3) allowed decay channel into a pair of charmed mesons.\[^9\] However since the \( \Psi''(3770) \) is only 40 MeV above the \( D\bar{D} \) threshold, the only OZI-allowed decay channels available are \( D^0\bar{D}^0 \) and \( D^+D^- \).

In view of the fact that the \( \Psi''(3770) \) and \( \Psi(3686) \) are so close in mass, it seems natural to expect that the decay width to non-\( D\bar{D} \) modes is in the vicinity of a few hundred keV. Therefore, in the past it has been assumed that the \( \Psi''(3770) \) decays predominantly to a pair of D mesons.\[^7\] However, there seems to be several lingering problems which suggest that the non-\( D\bar{D} \) modes should be looked at in more detail. These problems are briefly discussed in the next few paragraphs.

Several experiments have measured the total \( e^+e^- \) hadronic cross section at \( \sqrt{s} = 3.77 \) GeV, which is the sum of a Breit-Wigner for the \( \Psi''(3770) \) resonance, the radiative tails of the \( \Psi \) and \( \Psi' \), and the \( e^+e^- \) continuum annihilation which varies as the inverse of the squared center of mass energy.\[^10\]\[^11\]
Another method to measure $\sigma_{\psi(3770)}$ has recently been utilized by the Mark III.\textsuperscript{[12]} In this method the absolute branching fractions of the D mesons are calculated by taking the ratios of the number of double tags to the number of single tags:

$$S = 2NB\epsilon_S$$
$$D = NB^2\epsilon_D$$

where N is the number of $D\bar{D}$ pairs produced in the sample, B is the branching ratio to the selected decay mode, $\epsilon_S$ and $\epsilon_D$ are the reconstruction efficiencies for the single and double tags to the desired decay modes. Using these branching ratios along with the $\sigma \cdot B$ measurements, by Mark III, a value of $\sigma(\psi(3770)) = 5.0\pm 0.5$ nb is obtained. This measurement along with the direct measurements of the $\psi(3770)$ excitation curves are tabulated in Table 1-1. It is seen that the Mark III measurement based on the assumption that

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma_{\psi(3770)}$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Glass Wall</td>
<td>10.3±1.6</td>
</tr>
<tr>
<td>Crystal Ball</td>
<td>6.7±0.9</td>
</tr>
<tr>
<td>Mark II</td>
<td>9.3±1.4</td>
</tr>
<tr>
<td>Mark III</td>
<td>5.0±0.5</td>
</tr>
</tbody>
</table>

the $\psi(3770)$ decays only dominantly to $D\bar{D}$ pairs is significantly less than the average 8.8±0.8 nb obtained from the direct measurements. This suggests that either there are problems with the experiments or with the assumption that the $\psi(3770)$ decays predominantly into $D\bar{D}$ pairs.

Another source of concern has been the recent measurement by the CLEO collaboration, that claimed the observation of non-$B\bar{B}$ decays of $\Upsilon(4s)$ to inclusive $\psi$ states.\textsuperscript{[13]} $\Upsilon(4s)$ is the first $b\bar{b}$ bound state above the $B\bar{B}$ threshold, analogous to the $\psi(3770)$. Up to this claim, it had always been assumed that the $\Upsilon(4s)$ decays predominantly to a pair
of B mesons. CLEO claimed a branching fraction $BR (\Upsilon ( (4s) \rightarrow \Psi + X )) = (0.22 \pm 0.06 \pm 0.04) \%$ for $\Psi$'s with a momentum above 2 GeV/c. The momentum cutoff is simply because, B mesons from the decay of $\Upsilon (4s)$ cannot produce $\Psi$'s that have a momentum greater than 2 GeV/c. Therefore the observation of these fast $\Psi$'s is a sign that non-$B\bar{B}$ decays of the $\Upsilon (4s)$ is not negligible and must be studied further. One obvious implication of this was a rescaling of all measured B meson branching ratios. Although CLEO no longer sees this signal (as of this writing they have not retracted from their publication), it is important to look for the existence of non-$D\bar{D}$ decay modes of the $\Psi(3770)$.[14]

The goal is therefore to look for non-$D\bar{D}$ decay modes of the $\Psi(3770)$ with the data samples of the Mark III experiment. These decay modes can be classified into two parts. One class of decays are the charmonium transitions of $\Psi(3770)$. These are decays to other charmonium states such as $\Psi'' \rightarrow \Psi + \text{hadrons}$ and the radiative transitions $\Psi'' \rightarrow \gamma \chi_{cJ}$. Mark III has performed a couple of these measurements, measuring $\sigma_{\psi''} \times BR (\Psi'' \rightarrow \pi^+ \pi^- \Psi) = (0.011 \pm 0.005) nb$ and $\sigma_{\psi''} \times BR (\Psi'' \rightarrow \gamma \chi_{cJ}) = (0.083 \pm 0.042) nb$. [15] The other class of decays are channels that are not expected from the standard charmonium transitions. Since no specific theoretical predictions exist for such anomalous transitions, the best way to look for these OZI suppressed non-$D\bar{D}$ decay modes is to look for inclusive decays of the $\Psi(3770)$. In this thesis a search for three such inclusive channels, $\rho, \Lambda, \text{and } \phi$ is performed using the Mark III detector, which is described in Chapter 2.

To successfully perform the search for the above mentioned inclusive final states from the decays of the $\Psi''(3770)$, it is imperative to subtract the various sources of backgrounds which might also produce the same inclusive final state. There are three such major sources of backgrounds to subtract. The first is the production of the same final state from the decay of the $\Psi(3686)$, which can be radiatively produced at the $\Psi''(3770)$ energies. Chapter 3 will discuss this source in more detail. The second source of background is the production of the same final state by nonresonant $e^+e^-$ annihilation. The contribution from this source would ideally be estimated by scanning off resonance near the $\Psi''(3770)$. However, in the absence of such data samples, the background subtraction is performed by
using the Mark III data sample at $\sqrt{s} = 4.14$ GeV to scale the number of events observed at this energy to the lower $\sqrt{s} = 3.77$ GeV. One of the methods for carrying this procedure is to take advantage of the scale invariance exhibited by inclusive hadron production in $e^+e^-$ annihilation.\textsuperscript{[16]} This is motivated in section 1–4. Another method is to use the Lund Jetset Monte Carlo to perform the background subtraction.\textsuperscript{[17]} Chapter 4 will discuss this technique in more detail. The third source of background is the contribution from the decays of the D mesons, which are produced from the $\psi'(3770)$ decays. This source is subtracted by using the Mark III D Model Monte Carlo. The subtraction of this source is discussed individually for each the analyses. The analyses themselves will be presented in Chapters 5, 6, and 7. Chapter 8 will then present a summary of the various results obtained in this thesis.

1.2 The Charmonium Model

1.2.1 Spectroscopy

Since the charm quark is heavy, the $c\bar{c}$ separation in a bound state, which is of order $1/m_c$, is expected to be small. If the strong interaction is described by QCD, the strength of the interaction is weak at short distances because of asymptotic freedom, and therefore the nonlinearity in QCD will not be important.\textsuperscript{[18]} The situation is then very similar to that of QED; In analogy to positronium there should be a narrow resonance just below the threshold. Another simplification that can be made in the case of a heavy quark anti-quark system, such as the $c\bar{c}$, is the use of non-relativistic quantum mechanics to describe the slow moving quarks.

A simple model for the potential, describing the interaction between the quark and the anti-quark, can then be parameterized as:\textsuperscript{[19]}

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$$

\textsuperscript{(EQ 1-1)}

where $r$ is the relative distance between the quarks. The specific form for $V(r)$ is motivated by asymptotic freedom at short $c\bar{c}$ separations and quark confinement at large separations.
The third parameter in such a model is the quark mass, m. To solve the problem the Schrodinger equation in three dimensions must be solved:

$$\left[ -\frac{\nabla^2}{m} + V(\vec{r}) - E \right] \Psi(\vec{r}) = 0 \quad \text{(EQ 1-2)}$$

Since the potential of interest is a central potential the wave function $\Psi(\vec{r})$ can be separated into a radial and an angular part. The radial part of the Schrodinger equation can be written in a reduced form as:

$$\left[ \frac{d^2}{d\rho^2} - \frac{l(l+1)}{\rho^2} - \rho + \frac{\lambda}{\rho} + \zeta \right] \psi(\rho) = 0 \quad \text{(EQ 1-3)}$$

where the dimensionless length $\rho$, and eigenvalue $\xi$ are linearly related to $r$ and $E$ respectively, and $\lambda$ is just $\kappa(ma)^{2/3}$. After solving the equation the parameters $a$, $\kappa$, and $m$ are determined by fitting to, a) the experimental $\Psi-\Psi$ mass difference, b) electronic width of $\Psi$, and c) constraining $0.1 < \kappa < 0.4$ (in most model $\kappa$ is taken to be $(4/3)\alpha_s$). Table 1-2 shows the spectrum of low lying states predicted by this model together with the most likely candidates for these states.\textsuperscript{[20][21]} This naive model seems to predict the charmonium spectrum to a respectable degree. To break the degeneracy among the P and D states a more complicated potential model is used, which includes spin dependent forces.\textsuperscript{[20]}

<table>
<thead>
<tr>
<th>State $n^3L_J (J^P_C)$</th>
<th>Predicted Mass (MeV)</th>
<th>Candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S$_1$ (1$^-$)</td>
<td>3097 (input)</td>
<td>$\Psi(3097)$</td>
</tr>
<tr>
<td>1P$_J$ (0$^+$,1$^+_1$,2$^+_2$)</td>
<td>3475</td>
<td>$\chi_{0,1,2} (3522)$</td>
</tr>
<tr>
<td>2S$_1$ (1$^-$)</td>
<td>3686 (input)</td>
<td>$\Psi(3686)$</td>
</tr>
<tr>
<td>1D$_J$ (1$^-$, 2$^-$, 3$^-$)</td>
<td>3755</td>
<td>$\Psi''(3770) = 1^3D_1$</td>
</tr>
<tr>
<td>3S$_1$ (1$^-$)</td>
<td>4157</td>
<td>$\Psi(4040)$</td>
</tr>
<tr>
<td>2D$_J$ (1$^-$, 2$^-$, 3$^-$)</td>
<td>4204</td>
<td>$\Psi(4160) = 2^3D_1$</td>
</tr>
<tr>
<td>4S$_1$ (1$^-$)</td>
<td>4567</td>
<td>$\Psi(4415)$</td>
</tr>
</tbody>
</table>
1.2.2 \( ^3S_1 - ^3D_1 \) Mixing

The leptonic decay widths of the \( n^3S_1 \) states (with mass \( M \)), based on the non-relativistic charmonium model are given by:[20]

\[
\Gamma \left( n^3S_1 \rightarrow 1^+1^- \right) = 16\pi\alpha^2 Q_c^2 \frac{|\Psi(0)|^2}{M^2} \tag{EQ 1-4}
\]

This formula is taken in direct analogy from the positronium decay width. A calculation of the similar decay width for \( ^3D_1 \) in this model results in:[21]

\[
\Gamma \left( ^3D_1 \rightarrow 1^+1^- \right) = 200\alpha^2 Q_c^2 \frac{|R_D^*(0)|^2}{M^6} \tag{EQ 1-5}
\]

The numerical estimate for the electronic decay width of this state is small (120 eV) almost by a factor of 2 from 260 eV, the measured electronic decay width of the \( \Psi(3770) \).[4] Since the \( \Psi(3770) \) is close in mass to \( \Psi' \), which is believed to be a \( ^2S_1 \) state, the larger electronic decay width of the \( \Psi(3770) \) is believed to be the result of mixing between the \( ^2S_1 \) and the \( ^3D_1 \) levels:[8]

\[
\Psi' = \Psi_{2S} \cos\theta + \Psi_{1D} \sin\theta \tag{EQ 1-6}
\]

\[
\Psi'' = -\Psi_{2S} \sin\theta + \Psi_{1D} \cos\theta \tag{EQ 1-7}
\]

Using Equation 1-4 and Equation 1-5 the electronic widths for the mixed states \( \Psi' \) and \( \Psi'' \) can be calculated. The mixing angle is then determined by equating the ratio of these widths to the measured values. Using the Cornell potential model for \( Q\bar{Q} \) bound states, Kuang and Yan have calculated a mixing angle of \( \theta = -10^\circ \).[22] They also get another solution with a mixing angle of \( 30^\circ \). However this solution implies a larger rate for \( \Psi'' \rightarrow \Psi\pi\pi \) than that for \( \Psi' \rightarrow \Psi\pi\pi \) by a factor of 2.1, which is inconsistent with the experimentally measured ratio of 0.61±0.35.[4] [23] The \(-10^\circ \) solution on the other hand predicts a ratio of 1.3 which is closer to the experimental value.
1.2.3 Transition Rates

One can estimate various decay rates of the $\Psi^\prime$, within this simple non-relativistic model. The first process of interest is the $c\bar{c}$ annihilation which can proceed through different channel as depicted in Figure 1-1. To conserve color as well as charge conjugation symmetry these processes require at least three gluons or two gluons plus a photon or one photon before hadronization. Since $\alpha_s$ is small (~0.18) at these momentum transfer scales, higher order QCD corrections can be ignored to first order. The annihilation width can be written as a sum of the various channel:

$$\Gamma_{ann}(\Psi^\prime) = \Phi_{ggg} + \Phi_{\gamma g} + (2 + R_{cont}) \Gamma_{ee}$$

(EQ 1-8)

where $R_{cont}$ is the continuum $e^+e^-$ background in units of $\sigma (e^+e^- \rightarrow \mu^+\mu^-)$ at the $\Psi^\prime$. Since these decay rates of the $\Psi^\prime$ are proportional to the square of its wave function at the origin and are a consequence of the $2^3 S_1 - 3^3 D_1$ mixing, the above equation can be written in terms of the $\Psi^\prime$ annihilation width:

$$\Gamma_{ann}(\Psi^\prime) = \tan^2 \theta \Gamma_{ann}(\Psi) \left[ M_{\Psi^\prime}/M_{\Psi^\prime} \right]$$

(EQ 1-9)

Using the relation $\Gamma_{ee}(\Psi)/\Gamma_{ee}(\Psi^\prime) = \Gamma_{ann}(\Psi)/\Gamma_{ann}(\Psi^\prime)$ which is derived from the naive potential model, one can calculate $\Gamma_{ann}(\Psi^\prime)$:

$$\Gamma_{ann}(\Psi^\prime) = 0.6 \text{ keV}$$

(EQ 1-10)

where a $10^\circ$ mixing angle is assumed and $\Gamma_{ann}(\Psi) = 50 \text{ keV}$ is used.

The rates for electric dipole transitions, $E1$, are given by

$$\Gamma (\Psi^\prime \rightarrow \chi_J^0) = (16/243)(2J+1)\alpha k^3 [aE_{12;11}(k) \cos \theta - E_{20;11}(k) \sin \theta]^2$$

(EQ 1-11)

where $k$ is the photon energy, $a$ is a numerical factor which only depends on $J$, and in the small $k$ approximation, which is certainly valid here,

$$E_{nl;11} = \int_0^\infty j_0(kr/2) u_{11}(r) u_{nl}(r) rdr.$$

(EQ 1-12)

$j_0(kr/2)$ is the usual zeroth order spherical Bessel function and $u_{nl}(r) = rR_{nl}(r)$, where $R$ is the normalized radial wave function in the Schrodinger equation. [19]
Figure 1-1 \(c \bar{c}\) annihilation into gluons and photons before hadronization
Using the potential model (Equation 1-1), one can calculate these decay rates. The largest decay widths are obtained for the $\chi_0$ and $\chi_1$ transitions, which have a value of 370 keV and 150 keV respectively. Similar predictions are made for the $\Psi'$ dipole transitions using the same model (see Table 1-3). It can be seen that this model, despite its simplicity is in good agreement with the measured rates. The other transitions including the M1 transitions can be neglected since their decay widths are very much smaller compare to those of the $\chi_0$ and $\chi_1$ transitions.[20]

**TABLE 1-3E1 decay widths of $\Psi'$.**

<table>
<thead>
<tr>
<th>Transition</th>
<th>Theory (keV)</th>
<th>Experiment (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi' \rightarrow \gamma \chi_2$</td>
<td>27.</td>
<td>16±9</td>
</tr>
<tr>
<td>$\Psi' \rightarrow \gamma \chi_1$</td>
<td>38.</td>
<td>16±8</td>
</tr>
<tr>
<td>$\Psi' \rightarrow \gamma \chi_0$</td>
<td>44.</td>
<td>16±9</td>
</tr>
</tbody>
</table>

Among the other OZI-forbidden hadronic transitions of $\Psi''$, which are allowed by phase space and isospin conservation, such as transitions to $\Psi\pi\pi$, $\Psi\eta$, $\eta_c\omega$, and $\chi_0\pi\pi$, only the $\Psi\pi\pi$ transition is expected to occur with a reasonable decay width. The other transitions are suppressed by either small phase space, G-parity violation or p-wave transitions.

Recently Kuang and Yan have calculated the $\Psi\pi\pi$ transition of the $\Psi''$ using the Cornell potential model of charmonium taking full account of the $S - D$ mixing.[22] For a mixing angle of $10^\circ$, they get a decay width in the range of 30 – 160 keV depending the choice of coefficients in the soft pion matrix element.

Putting all the standard charmonium transitions together the decay width of the $\Psi''$ cannot be more than 1 MeV or so. Therefore, these standard transitions cannot account for the discrepancy in $\Psi''$ measured total cross section, which was stated at the beginning of this chapter.
1.3 The Okubo - Zweig - Iizuka Rule

The Okubo-Zweig-Iizuka (OZI) rule was proposed thirty years ago as a phenomenological explanation of some patterns in the decays of the $\phi$ meson.\cite{9} The OZI rule was first put in use to explain the following pattern of $\phi$ meson decay:\cite{4}

$$\Gamma (\phi \rightarrow 3\pi) \approx \frac{1}{5} \Gamma (\phi \rightarrow K\bar{K}) \approx \frac{1}{12} \Gamma (\omega \rightarrow 3\pi) \quad \text{(EQ 1-13)}$$

This relation holds despite the fact that phase space favors $\phi \rightarrow 3\pi$ over $\omega \rightarrow 3\pi$. In the quark model language, the decay $\phi \rightarrow K\bar{K}$ can proceed by the so called connected diagram of Figure 1-2a, since the strange quarks in the $\phi$ can simply fall into the final state mesons. On the other hand, $\phi \rightarrow 3\pi$ must proceed by a disconnected diagram (Figure 1-2b), since there are no strange quarks in the final state. The decay $\omega \rightarrow 3\pi$ proceeds via a connected diagram since both the initial and final states have the same flavor quarks.

In its simplest form the OZI rule states that the decays which proceed by disconnected diagrams are suppressed. The theory of QCD and asymptotic freedom seem to provide the dynamics which can explain the qualitative success of the OZI rule.\cite{18} In particular disconnected diagrams correspond to those processes where quarks annihilate into gluons. Since the inclusion of each gluon in a process introduces a factor of $\alpha_s$ in the matrix elements, it is thought that such processes should be suppressed when hard gluons are emitted. The running of $\alpha_s$ implies that the OZI rule becomes better with increasing meson mass.

The OZI rule is also successful in predicting the total decay width of the $\Psi$ systems. Since the $\Psi$ is below the threshold for decay to open charm hadrons, the $c\bar{c}$ pair must annihilate (Figure 1-3a) into gluons (at least three as discussed previously). Hadronic decays of the $\Psi$ are therefore suppressed by at least three powers of the strong coupling $\alpha_s (m_{\Psi}^2)$. On the other hand in the case of the $\Psi'$ the $c\bar{c}$ pair in the initial state falls into the $D\bar{D}$ final state vial the connected diagram of Figure 1-3b. The $\Psi'$ was therefore expected to have a width typical of strong processes. In fact the measured total width of the $\Psi'$ is about 24 MeV while that of the $\Psi$ is about 86 keV.\cite{4}
Figure 1-2 Quark model diagrams illustrating decays of the $\phi$ meson.
Figure 1-3 Feynman diagrams for charmonium decays.
Despite the qualitative successes of the OZI rule, no theory has yet emerged to give reliable quantitative predictions for OZI suppressed processes. One source of difficulty has been the large number of different intermediate states that could contribute to a suppressed process. An example for such mechanism is given by the decay sequence:

\[ \phi \rightarrow K^+K^- \rightarrow \rho \pi \]  

(EQ 1-14)

The direct transition to \( \rho \pi \) is forbidden by the OZI rule, but each of the individual steps is allowed to occur. The result is that this process occurs with a width that is more than five times that of the OZI suppressed process \( \phi \rightarrow 3\pi \).

An example of the quantitative failure of the OZI rule in predicting the suppression of a process was the error in the predicted width of the \( \Psi \).\[^{[24]}\] The \( \Psi \) width was predicted to be about 1.7 MeV, which is a factor of 20 larger than the actual width. The reason for this failure was that the measured \( \phi \rightarrow \rho \pi \) width was used as input and threshold effects were neglected. However, this decay mode is dominated by the two step mechanism, for which the OZI allowed \( K^+K^- \) channel is open. On the other hand the analogous \( D\bar{D} \) channel is not open in the case of the \( \Psi \), giving the \( \Psi \) a much smaller width. The point of this discussion is that when trying to use the OZI rule to predict quantitatively the rate for a process, one must consider various effects which might change the degree of the suppression by the OZI rule.

1.4 Scaling

One of the basic properties of electron hadron scattering is the scale invariance exhibited by the cross sections in the deep inelastic region.\[^{[16]}\] Inclusive hadron production in \( e^+e^- \) annihilation is expected to have similar properties. If scaling is assumed to hold, then the hadron inclusive production cross section can be written as:\[^{[26]}\]

\[ \frac{d\sigma}{dx} = 3 \sigma_{\mu \nu} x \left[ -F_1(x) + \frac{1}{6} x F_2(x) \right] \]  

(EQ 1-15)

Where \( x = 2E/\sqrt{s} \) is the scaling variable. \( E \) is the hadron energy, \( \sigma_{\mu \nu} = 4\pi\alpha^2/3s \), \( F_1(x) \) and \( F_2(x) \) are the structure functions of the photon in \( e^+e^- \) annihilation. It can be seen that
in this limit the shape of the cross section is independent of \( s \), and the magnitude of the cross section behaves like \( 1/s \). Since perfect scaling is approached in the limit of very high \( s \) (square of center of mass energy), it is believed that at lower energies scaling can be more evident in terms of some other variable.\(^{[27]}\)\(^{[28]}\) In the analyses presented in this thesis four different scaling variables are used to study the behavior of the inclusive channels under investigation. The different scaling variables are used as attempts to correct for finite particle mass effect as well as threshold effects on scaling behavior. The variables used are:

\[
x_E = \frac{2E}{\sqrt{s}} \quad (\text{EQ 1-16})
\]

\[
x_P = \frac{2P}{\sqrt{s}}
\]

\[
x' = \frac{P}{p_{\text{Max}}} \quad , \quad p_{\text{Max}} = \sqrt{E_{\text{Beam}}^2 - M_h^2}
\]

\[
\xi = \frac{E+P}{2E_{\text{Beam}}}
\]

where \( P, E \) and \( M_h \) are the momentum, energy and mass of the hadron respectively. \( x_P \) is more useful in inclusive studies that combine hadrons of different masses, such as charged particle inclusive production. \( x' \) gives a better measure of the fractional momentum carried by the hadron, while \( \xi \) is proposed to account better for the finite mass of the hadron.

Although scaling is not central to the physics goals of the thesis, it is nevertheless needed for the analyses presented in this thesis. Scaling is assumed to be valid for each of the scaling variable mentioned above, however, it is found that the results are fairly independent of the choice of a specific variable. Since scaling of the data is assumed, the only scale factor is simply the ratio of \( s \) at the two center of mass energies, which is just 1.20 for \( E_{\text{CM}} = 3.77 \text{ GeV} \) and 4.14 GeV.
Chapter 2

The Mark III Experiment and Data Processing

2.1 Introduction

The analyses presented in this thesis use data collected by the Mark III detector, a general purpose detector with large solid angle coverage designed for $e^+e^-$ physics at the electron positron storage ring SPEAR at the Stanford Linear Accelerator Center. SPEAR was designed to operate in the 3 to 5 GeV center of mass energy range. Electrons and positrons were injected from the two-mile long linear accelerator into the storage ring.

The Mark III detector, shown in Figure 2-1, was placed in the West Pit of SPEAR. The design of the detector was inspired by experiences with previous $e^+e^-$ detectors built for SPEAR: Mark I, Mark II, DELCO, and the Crystal Ball. The magnet steel for the detector was taken from Mark I, the original magnetic detector built for SPEAR.

The primary objective of the detector was to study exclusive final states of charmonium and charmed mesons in the 3 to 5 GeV center of mass energy range. The detector was optimized to provide,

- large solid angle coverage for detection of charged particles and photons,
- good particle identification of charged pions, kaons, and protons with momentum below 1 GeV/c,
- good detection efficiency for low energy photons, which was achieved by placing the shower counter inside the magnet.
Figure 2-1 The Mark III detector.
Particles traversing the detector from the interaction point to the outer components must first pass through the beryllium beam pipe, 15 cm in diameter, with 1.5 mm thick walls. The beam pipe is surrounded by the inner trigger chamber, also called Layer 1. This chamber was used for charged particle tracking and triggering purposes. Immediately after this chamber particles pass through the seven layers (Layer 2 to Layer 8) of the main drift chamber, which provide the bulk of charged particle tracking task.[30] The second layer (Layer 2) of the drift chamber is also used to provide energy loss measurements for particle identification. Surrounding the drift chamber is the Time of Flight (TOF) system, which consists of a series of 48 scintillation counters.[31] The TOF system is used to measure the time of flight of charged particles for particle identification. The electromagnetic shower counters which surround all the detector components mentioned so far, consists of three components.[32][33] The part encircling the TOF system is the barrel shower counter, while the other two parts at the ends of the drift chamber are the end cap shower counters. These shower counters provided the energy measurements for both charged and neutral particles. The shower counters are located inside the aluminum magnet coil, supplying a 0.4 Tesla magnetic field throughout the drift chamber for measuring the momentum of charged tracks. Finally, the above components are surrounded by two layers of muon counters used for detecting muons.

The readout electronics for the various subsystems consisted of sample and hold circuits as well as microprocessor controlled analog to digital converters for digitizing signals and applying various pedestal and gain corrections before delivering the data to a VAX 11/780 computer.[34]

In the rest of this chapter, each of the above mentioned components of the detector is described in more detail. This chapter also presents and discusses the processing of the raw data collected with these subsystems.
2.2 The Drift Chambers

The Mark III drift chambers consists of two sections: an inner trigger drift chamber near the beam pipe and an outer main drift chamber.

The trigger chamber (Figure 2-2) is a small low mass cylindrical drift chamber with an inner radius of 9.2 cm, an outer radius of 13.7 cm, a length of 110 cm, and a solid angle coverage of 98% of 4π steradians. The chamber consists of four sublayers, each with 32 drift cells. Each drift cell consists of one 38 μm stainless steel sense wire bordered on each side by 178 μm BeCu field wires in a gas mixture of 70% argon and 30% methane. The wires are terminated with amplifiers at both ends. When a charged track passes through a cell, a pulse will be generated in the sense wire. Since the wire has non-zero resistance, the location of the track in Z direction can be obtained by the relative amplitude of the pulses at the two ends of the wire.

The chamber is designed to be used for trigger purposes by having a (1/2) cell offset between adjacent wire planes. To the extent that the drift velocity is constant, the sum of drift times (\(t_1 + t_2\)) from adjacent wire planes should be a constant offset from the beam crossing time for radial tracks originating from the interaction point. Out of time cosmic rays, or looping tracks of very low momentum such as those from beam gas events will have a displaced time sum. The time gate for acceptable (\(t_1 + t_2\)) is 100 nsec wide, while the time between adjacent beam crossings is 780 nsec. This translates into an almost eight fold reduction in trigger rate. Figure 2-3 shows the distribution of (\(t_1 + t_2\)) for events satisfying the trigger requirements. It is seen that the hadronic events occur within the 100 nsec interval, and in fact peak at \(t = 0\); On the other hand the cosmic ray events are distributed uniformly over the gate interval.

Immediately surrounding the inner trigger chamber is the main drift chamber consisting of seven layers (Layer 2-8) of tracking cells (Figure 2-4), covering a solid angle of 85% of 4π steradian. The chamber has an inner radius of 18.5 cm and an outer radius of 108.6 cm. The length of Layer 2 is 183 cm long while the remaining six layers are 239 cm in length. The gas used in the chamber was a mixture of 89% argon, 10% CO₂ and 1% methane.
Figure 2-2 The transverse view of the inner trigger drift chamber.
Figure 2-3 The distribution of \((t_1 + t_2)\) for events that have satisfied the trigger requirements (therefore they have at least one track within the time gate).
Figure 2-4 End view of 1/16th of the main drift chamber.
Layer 2 is made of twelve sense wire planes, on which both drift times as well as pulse heights are measured. The latter measured to determine energy loss by charged tracks for particle identification purposes.

Layer 3 through 8 is designed to have each of its cells approximately of equal size. The layers are divided into 16*N cells, where N is the layer number. Each cell, which is about 5.3 cm wide, consists of three 20 \( \mu \text{m} \) diameter tungsten sense wires and two 57 \( \mu \text{m} \) diameter stainless steel guard wires. Layers 4 and 6 are stereo layers at an angle of 7.7° and −9.0°, respectively, allowing three dimensional charged track reconstruction of momenta. Additional Z information is obtained from Layers 3, 5, and 7 by charge division in the guard wires.

To resolve the left-right ambiguity in the track trajectories through the cells, sense wires are staggered by \( \pm 400 \mu \text{m} \) in \( \phi \). This is achieved by looking at the sign of \( \Delta \), which is defined as:

\[
\Delta = V_{\text{drift}} \left( \frac{t_1 + t_3}{2} - t_2 \right)
\]

where \( V_{\text{drift}} \) is the drift velocity and \( t_1, t_2, \text{and } t_3 \) are the measured times on the three sense wires. The sign of \( \Delta \) determines through which half of the cell the track has passed. The distribution of \( \Delta \) for all cells in layer 5 is shown in Figure 2-5. Two clear and well resolved peaks corresponding to tracks on the two sides of the cell are present in the figure.

### 2.3 The Time of Flight System

The time of flight (TOF) system (Figure 2-6) consists of 48 Nuclear Enterprises Pilot F plastic scintillators, 15.6 cm wide, 5 cm thick and 3.2 m long. The counters are mounted parallel to the beam at a radius of 1.2 m, covering a solid angle of 80% of 4\( \pi \) sr. Light generated from a particle passing through a counter is transmitted to the ends of the counters via the ultraviolet transmitting plexiglass light guides. The light guides bring the light outside of the magnet flux return steel to 2 inch Amperex XP2020 phototubes.
Figure 2-5 The distribution of $\Delta$. 
Figure 2-6 The time of flight system.
The time measurements are made relative to beam crossing signals, derived from pick-off electrodes in the beam pipe near the detector. The times when the pulse from the photomultiplier crosses two different discriminator thresholds are recorded from both ends of the struck counters. The system is calibrated online by a N\textsubscript{2} laser which sends pulses to the counters via fiber optic cables. Offline corrections are determined by using Bhabha or dimuon events, which have tracks arriving at known times relative to beam crossings. Other corrections to the raw times such as time pedestal subtraction, and Z position of the track in the TOF counters are determined separately for each counter.

### 2.4 The Shower Counters

The Mark III shower counters were placed inside the magnetic coil, which resulted in a reduction of the amount of material before the calorimeters. This design aspect of the counters enabled the detector to be much more sensitive in detecting low energy photons and electrons, and hence improved the efficiency for reconstruction of π^{0} and η mesons.

The shower counters consists of three components, a barrel and two endcaps providing a solid angle coverage of 94\% of 4π sr. Each component consists of 24 layers of proportional tubes separated by 0.28 cm, or (1/2) radiation, length Pb sheets. The coordinate along the wire direction is determined by charge division on the stainless steel sense wires. A gas mixture of 80\% argon and 20\% methane is used.

The barrel shower counter (Figure 2-7) is divided in φ by thin aluminum I-beams into 320 proportional tubes per layer, which results in a resolution of σ_{0} = 7mr. The 46 μm sense wires, with a length of 3.5 m, have 2000 Ω resistance and yields by the method of charge division an axial resolution of σ_{0} = 20mr.

The endcap shower counters consist of 24 layers of 0.5 radiation length lead separated by aluminum proportional tubes 2.71 cm wide and 1.17 cm thick. In the endcaps the proportional cells run vertically. The performance of the endcaps is similar to that of the barrel.
Figure 2-7 The barrel shower counter.
2.5 The Magnet

The magnetic field is essential in determining the momentum of charged particles. The Mark III magnet provides a magnetic field of 0.4 Tesla at the center of the tracking chambers. The magnet coil is wound with four layers of 5 cm by 5 cm aluminum conductor. Each conductor has a 2.5 cm diameter hole through which cooling water flows. The power consumption of the coil is 1 MW. Two small compensator magnets are built near the beam axis at ±2m from the interaction region. These magnets compensate for the effect of the axial magnetic field on the beam.

The magnetic field was mapped by Hall probes before the detector was installed. A total of 17 parameters were required to describe the field to an accuracy of about 0.2% over the volume of the tracking chamber.

2.6 The Muon System

Since the pion and muon masses are very close to one another, it is very difficult to separate them by TOF methods. However, pions have a relatively large interaction cross section with material, compare to that of muons. Muons can therefore go through large amounts of material before interacting with the material. Using this difference the muon system of Mark III separates muons from pions.

The muon detector is located outside of the magnet flux return steel. The detector consists of two layers of proportional tubes separated by 12 cm of steel, which covers 65% of the 4π solid angle. The system consists of 1080 proportional tubes of 2.5 cm radius and 420 cm length. The sense wires located at the center of the tubes provide the Z position of the hits by charge division. The sense wires operate at 2700 V with a gas mixture of 80% argon and 20% methane.

Muons with momentum below 600 MeV/c do not reach the muons system. The efficiency of the counters has been measured to be 99% for muons with a momentum greater than 800 MeV/c.
2.7 The Event Trigger

The trigger system of the Mark III uses information from the drift chamber and the time of flight systems to distinguish \( e^+e^- \) physics events from cosmic and beam gas events.\[^{35}\]

The beam crossing rate at SPEAR is 1.28 MHz = 1/(780 nsec). The trigger consists of two stages: Level 1 and Level 2. If a trigger is not satisfied at either level the electronics is reset for the next beam crossing. If on the other hand a trigger is satisfied then an interrupt is generated and further triggers are inhibited while the events is logged to tape, which takes approximately 30 msec.

The Level 1 trigger uses the inner trigger chamber and the TOF system information. The trigger system simultaneously looks for “two-track” and “one-track” configurations. If either of them is satisfied a Level 2 trigger is started. A “two-track” trigger is satisfied if two charge tracks are found in the inner trigger chamber. A “one-track” trigger, on the other hand, requires one track in the inner trigger chamber and at least one TOF hit. The decision is made within 590 nsec after the beam crossing. This allows enough time for the capacitors in the sample and hold electronics to discharge before the next beam crossing, if the events fails to satisfy the trigger requirements. Events that do fail do not contribute to the dead time.

In the Level 2 trigger, a simple track reconstruction is performed using hits from Layer 1, 3, and 5 of the drift chamber. Because the maximum drift time in the main drift chamber is about 550 nsec, this information arrives too late to be used in the first level trigger. Programmable logic array integrated circuits are used to identify coincidences between cells in the three layers. The basic idea of the algorithm is illustrated in Figure 2-8. Starting with each hit cell in layer 5, the Level 2 trigger looks for valid patterns of hit cells in the other two layers. The valid patterns are all triple coincidences of the hit cells for tracks with a transverse momentum greater than 50 MeV/c, where a hit cell has signals from at least two out of three sense wires. Both a one-track trigger and a two-track trigger are implemented in the experiment.
Figure 2-8 Cartoon of the track finding algorithm used in Level 2 of trigger. Tracks are required to have hit cells in layer 1, 3, and 5.
The trigger rate at the \( \psi(3770) \) was 3.5 Hz with the Level 2 trigger. This results in about 10% dead time. Analysis of the data at the \( \psi(3686) \) shows that the trigger efficiency is about 97%.

### 2.8 The Data Samples

To measure the inclusive decay rates of the \( \psi(3770) \), the \( 9.56 \pm 0.48 \, pb^{-1} \) \( \psi(3770) \) data sample of Mark III is used. Since the analyses require the subtraction of backgrounds from \( e^+e^- \) continuum production as well as from radiative \( \psi(3686) \) production, the \( 6.30 \pm 0.46 \, pb^{-1} \) data set at \( \sqrt{s} = 4.14 \, GeV \) and the 1982 data set containing about 150,000 \( \psi(3686) \) events are utilized as well. Table 2-1 lists the data samples used in the studies presented in this chapter.

<table>
<thead>
<tr>
<th>Time</th>
<th>( E_{CM} )</th>
<th>Luminosity or Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982 Fall</td>
<td>( \psi(3684) )</td>
<td>( \sim 150 , K ) hadronic events</td>
</tr>
<tr>
<td>1982 Fall</td>
<td>( \psi(3770) )</td>
<td>( \sim 1.80 , nb^{-1} )</td>
</tr>
<tr>
<td>1983 Spring</td>
<td>( \psi(3770) )</td>
<td>( \sim 3.80 , nb^{-1} )</td>
</tr>
<tr>
<td>1984 Winter</td>
<td>( \psi(3770) )</td>
<td>( \sim 3.96 , nb^{-1} )</td>
</tr>
<tr>
<td>1986 Winter</td>
<td>4.14 GeV</td>
<td>( \sim 6.30 , nb^{-1} )</td>
</tr>
</tbody>
</table>

### 2.9 Monte Carlo Event Generators

Monte Carlo event generators are used in this thesis to estimate efficiencies and study backgrounds. After events are generated, detector simulation is performed on each track.

The two generators used most frequently in this thesis simulate the following reactions:

- \( e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D} \)
- \( e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s} \) (g)
The first process is simulated by the Mark III $D\overline{D}$ event generator, which produces pairs of $D^-$ and $D^+$ mesons with a $\sin^2\theta$ angular distribution. Each D meson is then decayed randomly according to a dictionary containing the branching ratios for various decay modes. Most of the entries in the dictionary are measured branching ratios. The remaining channels are adjusted to produce the inclusive multiplicity and momentum distributions observed in the data.\cite{36}

The second reaction listed above is simulated with the Lund Jetset 6.2 generator, which is based on the Lund string fragmentation model. This generator is used to estimate the ratios of the efficiencies at two center of mass energies, 3.77 GeV and 4.14 GeV. It is also used to find the ratio of the number of various final states at the two center of mass energies.

After events are generated, the final state particle four vectors are propagated through the detector simulation. Various detector effects are taken into account such as dead channels, and subsystem resolutions and efficiencies. Energy loss, multiple Coulomb scattering, and hadronic interactions in the detector material are included as well.

2.10 The Filter

Despite the fact that the Mark III trigger discards events that are produced by beam gas and cosmic ray events, only 1% (30% at the $\Psi'$ resonance) of the logged data consists of interesting $e^+e^-$ events.\cite{37} To further reduce the number of undesired events and facilitate the offline data reconstruction, the data is processed by a filter program, which categorizes events as either Bhabhas, dimuons, hadrons, cosmic rays or "junk".\cite{38} The program then discards the cosmic ray and "junk" events.

The filter program first utilizes the TOF and muons system information to distinguish dimuon events. It then looks at the shower counter information and labels events as either Bhabhas, hadronic, cosmic rays or "junk". This is done on the basis of the number of showers, the shower energy distribution and the total shower energy. Before discarding the cosmic ray and "junk" events, they are searched for tracks by a fast track finder. If these events contain more than two tracks they are kept, otherwise they are discarded.
The efficiency of the filter for retaining $e^+e^-$ events was calculated to be about 99%, by performing various checks such as scanning visually large samples of rejected events and varying the selection cuts.

2.11 Drift Chamber Reconstruction

After an event passes the filter program, event reconstruction programs take the raw data and after applying the necessary corrections, transforms it into a suitable form for physics analysis.

The first step in this process is to find charged particle tracks in the drift chamber. This is accomplished by finding tracks using a fast and efficient track finding algorithm which emulates the track finding hardware of the trigger. Local drift cell information is used to resolve confusions such as left-right ambiguities. A fast circle fitter is used to provide starting values for the full helix fit parameters. Information on the Z position of the track is then sought, by looking at the stereo layers 4 and 6. Tracks that contain this information (80%) are used to find the position of the event vertex. For those tracks that have only one stereo layer information, the Z information is found by using the stereo layer and the event vertex. For those tracks that do not have any stereo layer information, the event vertex position and charge division from layers 1, 3, 5, and 7 are used. Good tracking efficiency is achieved for tracks which reach layer 3, covering 94% of $4\pi$ solid angle.

Finally the track momentum is determined by an iterative fit to a series of linked helices. Track trajectories are parametrized by five helix parameters: $\phi = \text{azimuthal direction of } \hat{p}$ at the closest point of approach to the z-axis; $\kappa = 1/p_{xy}$; $s = \tan \lambda$, where $\lambda$ is the dip angle; $\xi = x \sin \phi - y \cos \phi = \text{signed distance of closest approach to the z-axis}$; and finally $\eta = z$ position at the point of closest approach.

The momentum resolution of the drift chamber is given by:

$$\sigma_p/p = 0.015\sqrt{1+p^2}$$
where $p$ is in GeV/c.\textsuperscript{[40]} The first term is the contribution from multiple scattering in the material of the detector before the drift chamber. The angular resolutions are:

\[
\sigma_\phi = 0.002
\]
\[
\sigma_{\tan \lambda} = 0.011
\]

As already mentioned, Layer 2 of the drift chamber is also used to obtain dE/dx ionization information for particle identification. After correcting the raw pulse heights for various effects due to the electronics and pressure and temperature fluctuations in the gas, the energy loss is then determined from an average of the lowest 75\% of the pulse heights. Particles are identified by looking at the quantity:

\[
x_i \equiv \frac{(E^{pred}_i - E^{meas})}{\sigma}
\]

where $E^{pred}_i$ is the predicted energy loss for a mass hypothesis $i$, $E^{meas}$ is the measured energy loss, and $\sigma$ is the resolution in $E^{meas}$, which depends on the number of pulse height measurements and is determined from Monte Carlo simulations. The predicted energy loss is calculated using the Landau-Sternheimer formula:\textsuperscript{[41]}

\[
\frac{dE}{dx} = \left( \frac{N}{\beta^2} \right) \left[ 9.0 + \ln \gamma^2 - \beta^2 - \delta \right]
\]

where $\delta$ parametrizes the density effect and $N$ is a normalization constant. A track is said to be consistent with the mass hypothesis $i$ if $-3.0 < x_i < 4.5$. K/$\pi$ separation is possible up to about 600 MeV/c.

In the analyses presented in this thesis the dEdx information for a charge track is used if it has:

- $|\cos \theta| \leq 0.85$ where $\theta$ is the polar angle of the track with respect to the beam axis,
- momentum $\leq 550$ MeV/c,
- greater than or equal to 6 dEdx hits in Layer 2.
2.12 Time of Flight Reconstruction

For reconstructing the raw TOF data, the timing signals from both ends of each counter are first calibrated using samples of Bhabha events collected by the filter program. Corrections are made for various effects such as finite light propagation time in the scintillator, time walks associated with varying pulse heights, and timing offsets due to cable lengths, etc. Time of flight hits are then associated with tracks reconstructed in the drift chamber. For each such combination a \( \chi^2 \) is calculated between the \( z \) positions measured by the time of flight and by the drift chamber. This \( \chi^2 \) is then used to label the quality of the time of flight information for that particular track. In the analyses which will be presented in this thesis the time of flight information is used for a track provided the quality of the time of flight hit falls in one of the following categories:

- One drift chamber track in the counter with good \( \chi^2 \).
- Two drift chamber tracks in the counter with good \( \chi^2 \) for this track.
- The drift chamber track entered the counter far from a cluster of other tracks going through the same counter.
- One drift chamber track in the counter. Either both ends of the counter fired with one end having too small a charge, or one end did not fire at all. In the first case both ends are used, while in the second case only one end is used.

To identify charged tracks the measured time of flight \( T^{\text{meas}} \) is compared with the predicted time

\[
T_i^{\text{pred}} = \frac{L \sqrt{M_i^2 + p^2}}{p c}
\]

for the mass hypothesis \( i \), where \( M_i \) is the hypothesized mass, and \( L, p \) are the path length and momentum determined from the drift chamber reconstruction.

In this thesis particles are identified by looking at the time of flight weights:
\[ w_{t_i} \equiv \exp \left\{ -\frac{1}{2} \frac{(T_{i}^{\text{pred}} - T_{i}^{\text{meas}})^2}{\sigma_i^2} \right\} \]

where the time residual uncertainty, \( \sigma_i \), includes the time resolution of the individual TOF counter and the uncertainty on the predicted time resulting from the drift chamber resolution. The time of flight resolution obtained for hadrons is about 200 psec. At least 3\( \sigma \) \( \pi/K \) and a 3\( \sigma \) \( K/p \) separation is achieved for tracks up to 0.8 GeV/c and 1.2 GeV/c respectively. Figure 2-9 shows this in a scatter plot of \( \beta \) verses momentum for tracks in the data sample.

In this thesis TOF information is used for a track provided the track meets the quality criteria mentioned above. The track is also required to have \( |\cos \theta| \leq 0.80 \) where \( \theta \) is the polar angle of the track with respect to the beam axis.

### 2.13 Shower Counter Reconstruction

The shower reconstruction involves the identification of hits in the shower counters. Charge division is used to determine the shower position along the proportional tubes. The total energy deposited in each shower is obtained by integrating the collected charge.

The shower counter performance is studied using electrons from Bhabha events and photons from kinematically constrained \( J/\Psi \rightarrow \pi^+ \pi^- \pi^0 \) events. The counters are fully efficient for photons down to 100 MeV in energy. The energy resolution is well parameterized by

\[
\frac{\sigma_E}{E} = \frac{18\%}{\sqrt{E}}
\]

where \( E \) is in GeV.
Figure 2.9 $\beta$ versus momentum scatter plot for tracks in the data sample. Clear $\pi$, $K$ and $p$ bands are seen.
2.14 The Muon Detector Reconstruction

The muon detector reconstruction begins by projecting drift chamber tracks through the time of flight counters, shower counters, magnet coil and into the muon system. To account for multiple scattering the amount of material traversed by the track is computed. The muon tubes are searched within $6\sigma$ of the projected track. A high momentum track is identified as a muon if it is detected in both layers of the muon system. The muon system classifies the tracks in one of three categories: the track is either a muon or it is not a muon, or the muon system can not tell whether the track is a muon or not.
Chapter 3

Ψ(3686) Normalization

3.1 Introduction

The Ψ(3686), also known as the Ψ', is a $J^{PC} = 1^{-} c\bar{c}$ bound state with a high peak production cross section of about 10±2μb. The Ψ' has a mass which is only 84 MeV below the Ψ'' mass. It is therefore expected that many Ψ''s will be produced at $\sqrt{s} = 3.77$ GeV by the process of initial state radiation. Since the purpose of this thesis is to search for non-charm decays of the Ψ'', the production of the same final state by radiatively produced Ψ' introduces a potential source of contamination to the desired signal (The low energy radiated photon is hard to detect).

The branching fractions of the desired inclusive non-charm final states from Ψ' decays are estimated by searching for these final states in the Ψ' data set of Mark III. Then, to estimate the contamination in the Ψ'' data set due to radiatively produced Ψ' decays to the same final states, the total number of Ψ''s produced at $\sqrt{s} = 3.77$ GeV must be known.

It is, thus, the aim of this chapter to calculate the number of Ψ''s produced in the Ψ'' data set at $\sqrt{s} = 3.77$ GeV. Ψ''s are detected through its decay mode ($\Psi' \rightarrow \Psi \pi^+ \pi^-$), where the Ψ then decays to a pair of muons ($\Psi' \rightarrow \mu^+ \mu^-$). As a cross check of the analysis technique, the number of Ψ''s is also determined by the same Ψ' decay channel ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) but with the Ψ decaying to a pair of electron-positron ($\Psi \rightarrow e^+ e^-$).

This particular Ψ' decay model is chosen for two reasons. First the branching fraction for this decay mode is fairly high BR ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) = (32.4 ± 2.6)% , and second the final products are all charged tracks.
3.2 Event Selection

Radiatively produced $\Psi \pi^+ \pi^-$ events, where the $\Psi$ decays through either ($\Psi \rightarrow \mu^+ \mu^-$) mode or ($\Psi \rightarrow e^+ e^-$) mode, are selected by requiring the events to have:

- four charged tracks,
- net charge of zero,
- $x y_{\text{vertex}} \leq 0.05$ m and $|z_{\text{vertex}}| \leq 0.1$ m
- each track satisfy a good helix fit and each track must have z information.

Where $x y_{\text{vertex}}$ and $z_{\text{vertex}}$ are the primary vertex positions in the xy plane and along the z-axis respectively.

Since the leptons have very high momentum and the pions have very low momentum, events are required to have two tracks with momentum greater than 1.0 GeV/c and two tracks with momentum less than 0.6 GeV/c. The two low momentum tracks (candidate pions) are further required to have opposite charges.

Table 3-1 shows the number of candidate events remaining after each one of the above cuts are applied at $\sqrt{s} = 3.77$ GeV, starting with 668119 events. A similar table is shown for the Monte Carlo results in Section 3.5, where the detection efficiency for this decay channel is calculated. Since most of the events with four charged tracks have comparable momentum with each other (due to phase space generation), requiring two of them to have high momentum, greater than 1.0 GeV/c, drastically reduces the number of candidate events as indicated in Table 3-1.
3.3 Particle Id

To distinguish the $\Psi$ decay mode ($\Psi \rightarrow \mu^+\mu^-$) from ($\Psi \rightarrow e^+e^-$), muons must be separated from electrons. This is accomplished using the Mark III muon system and also by using the E/P method where E and P are the measured energy and momentum of the charged particle in question.

### 3.3.1 Using the Muon System

The muon system, described in Chapter 2, provides three possibilities for a charged track. A track is placed in one of the following three categories depending on its direction as determined by the drift chamber and also depending on hits in the muon chambers:

- Not a muon,
- Possibly a muon,
- Definitely a muon.

When searching for the ($\Psi \rightarrow \mu^+\mu^-$) mode, the two high momentum tracks are required not to fall in the first category described above, i.e., they are required not to be rejected by the muons system as possible muons. This choice for identifying muons has the benefit of
keeping the detection efficiencies high (as can be seen in Table 3-2 of Section 3.5), and is followed by distinguishing the electron from the muon by measuring E/P. After this requirement 1641 events are retained in the $\mu\mu$ channel.

3.3.2 Using the E/P Method

High energy electrons can be separated from muons and pions by calculating their E/P. High momentum muons and pions, which are minimum ionizing particles, deposit very little energy in the shower counter compare to an electron with the same momentum. This effect is shown for Monte Carlo generated muon and electron tracks in Figure 3-1.

When searching for the ($\Psi \rightarrow \mu^+\mu^-)$ mode, the two high momentum tracks are required to have an $E/P < 0.45$, where the energy $E$ is measured in units of GeV and $P$ is measured in units of GeV/c. In contrast when searching for the ($\Psi \rightarrow e^+e^-$) mode, the two high momentum tracks are required to have an $E/P > 0.45$. Figure 3-2 shows a scatter plot of E/P for the two high momentum tracks for events which pass the general event selection of 3.2. There is a clear separation of events in two categories, one with low (E/P) and one with higher (E/P). After these requirements 783 events are retained in the $\mu\mu$ channel and 2066 events are retained in the ee channel. In Figure 3-2 there are some events which have one high (E/P) and one low (E/P); However as will be discussed in the next section, these events have a $\pi^+\pi^-$ recoil mass that is outside the $\Psi$ mass region.

3.4 Kinematic Fits to the Desired Final State

After the general event selection and the particle identification requirements the remaining events are kinematically fit to the desired final states. In the case of the $\Psi$ decaying to a pair of muons ($\Psi \rightarrow \mu^+\mu^-$) the events are fit to ($\gamma\mu^+\mu^-\pi^+\pi^-$) final state where the $\gamma$ is allowed to be missing. After a successful fit (1-C) events with prob($\chi^2$) $\geq 0.1$ are retained. When searching for events with $\Psi$ decay mode ($\Psi \rightarrow e^+e^-$), the events are fit to ($\gamma e^+e^-\pi^+\pi^-$) final state, where the $\gamma$ is allowed to be missing. Again after a successful fit, events with prob($\chi^2$) $\geq 0.1$ are retained. Figure 3-3 shows the prob($\chi^2$) distribution for both final states. The $\pi^+\pi^-$ recoil mass distributions for the events retained are shown...
Figure 3-1 (E/P) distribution for Monte Carlo generated a) muons, and b) electrons. Both the muons and the electrons are uniformly generated in the momentum range [1.0-2.2] GeV/c.
Figure 3-2 Scatter plot of (E/P) for the two high momentum tracks for events that pass the general event selection. Two distinct groups are visible. The one with the lower (E/P) is believed to be muons and the one with the higher (E/P) is believed to be electrons (positrons).
Figure 3-3 $\chi^2$ distribution for $\gamma\Psi\pi\pi$ events where the high momentum tracks are candidate a) dimuons, and b) electron-positron pair. The arrows correspond to the 10% cut on $\text{prob}(\chi^2)$. 
Figure 3-4 $\pi^+\pi^-$ recoil mass distribution of events passing the kinematic fit cuts where the $\Psi$ decays to a) dimuons, and b) electron-positron.
in Figure 3-4, where a clear $\Psi$ peak is visible. 418 events pass this requirement in the $\mu\mu$ channel, while 798 events pass in the $ee$ channel. Events with a $\pi^+\pi^-$ recoil mass in the range $[3.0-3.2] GeV/c^2$ are retained as candidate $\Psi'$ events. The number of $\Psi'$ events will be determined after fitting the recoil mass distribution with an appropriate function as will be described shortly.

As mentioned in the previous section some events had one high momentum track with a high (E/P) and one high momentum track with a low (E/P) (see Figure 3-2). If the (E/P) cuts are not imposed and the events are kinematically fitted to the desired hypothesis (either with the $\mu\mu$ channel or the $ee$ channel), then a scatter plot of (E/P) for the two high momentum tracks will reveal that most of these peculiar events are rejected once the $\pi^+\pi^-$ recoil mass is required to be consistent with the $\Psi$ mass (see Figure 3-5).

3.5 Detection Efficiency

The overall detection efficiency is calculated by generating ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) Monte Carlo events, where the $\Psi'$ is produced radiatively at $\sqrt{s} = 3.77$ GeV. The final states of interest is then generated in two steps. First the ($\Psi' \rightarrow \Psi + X$) is generated with an isotropic angular distribution, using the $X$ mass distribution.$^{[42]}

$$
\frac{dN}{dm_X} \propto \left( \frac{m_X^2 - 4m_X^2}{2} \right)^5 \left( \frac{m_{\Psi'}^2 - m_{\Psi}^2 - m_X^2}{2} \right)^2 \left( m_{\Psi'}^2 - m_X^2 \right)^{1/2} (EQ 3-1)
$$

Then $X$ is decayed isotropically to $\pi^+\pi^-$, while the $\Psi$ is decayed with a $(1 + \cos^2 \theta)$ distribution to a pair of leptons.$^{[43]}$ It should be noted that all angles are defined in the rest frame of the decaying particle with the $z$ axis defined by the incident $e^+e^-$ direction.

The $m_X$ distribution is derived from a $(2S \rightarrow 1S + \pi^+\pi^-)$ transition in the framework of the multipole expansion of QCD with the Cornell potential model to describe the quark-antiquark interaction.$^{[19]}$ The predicted distribution matches very well with the measured distribution in both the ($\Psi(2S) \rightarrow \Psi(1S) \pi^+\pi^-$) transition and the ($\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+\pi^-$) transition.$^{[44]}$ $^{[45]}$
Figure 3.5 Scatter plot of \((E/P)\) for the two high momentum tracks for events that pass the general event selection as well as the kinematic fit requirements. These events are also required to have a \(\pi^+\pi^-\) recoil mass that is consistent with the \(\Psi\), i.e., in the [3.09-3.11] GeV range.
After generating the events, the tracks are then passed through the detector simulation and the events are reconstructed. Figure 3-6 shows a scatter plot of (E/P) for the two high momentum tracks for events that pass the general event selection discussed earlier.

After the general event selection and the particle identification requirements the remaining events are kinematically fit, using the Mark III standard kinematic fitting package TELE-SIS, to the desired final states as discussed earlier. The prob($\chi^2$) distribution of the fits for both final states ($\gamma \mu^+ \mu^- \pi^+ \pi^-$ and ($\gamma \ e^+ e^- \pi^+ \pi^-$) is shown in Figure 3-7. After accepting events with prob($\chi^2$) $\geq$ 0.1, the $\pi^+ \pi^-$ recoil mass distributions are plotted in Figure 3-8. For comparison the $\pi^+ \pi^-$ invariant mass distribution for events passing the kinematic fit cut and belonging to the signal region of

$3.0 \leq \pi^+ \pi^- \text{ Recoil Mass} \ (\text{GeV}/c^{**2}) \leq 3.2$ is plotted in Figure 3-9 for both the data sample and the Monte Carlo sample. It can be seen qualitatively that the comparison is fairly good for both the ee and $\mu\mu$ decay modes of the $\Psi$.

Table 3-2 shows the number of Monte Carlo events remaining after each cut in the analysis is applied starting with 10000 events:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Events ($\mu\mu$)</th>
<th>Events (ee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four charged tracks</td>
<td>7704</td>
<td>7852</td>
</tr>
<tr>
<td>Net charge of zero</td>
<td>7636</td>
<td>7789</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>7563</td>
<td>7717</td>
</tr>
<tr>
<td>Track quality</td>
<td>7361</td>
<td>7527</td>
</tr>
<tr>
<td>Two high and two low momentum tracks</td>
<td>7285</td>
<td>7209</td>
</tr>
<tr>
<td>Oppositely charged low momentum tracks</td>
<td>7285</td>
<td>7209</td>
</tr>
<tr>
<td>Muon system</td>
<td>7066</td>
<td>-----</td>
</tr>
<tr>
<td>(E/P)</td>
<td>7066</td>
<td>7165</td>
</tr>
<tr>
<td>Kinematic fit</td>
<td>5865</td>
<td>5942</td>
</tr>
</tbody>
</table>
Figure 3-6 Scatter plot of $(E/P)$ for the two high momentum tracks for Monte Carlo events that pass the general event selection. a) $\Psi$ decaying to dimuons and b) $\Psi$ decaying to electrons and positrons.
Figure 3-7 $\chi^2$ distribution for Monte Carlo generated $\gamma \Psi \pi \pi$ events where the $\Psi$ decays to a) dimuons, and b) electron-positron. As before the arrows correspond to the 10% cut on prob($\chi^2$).
Figure 3-8 $\pi^+\pi^-$ recoil mass distribution of MC events passing the kinematic fit cuts where the $\Psi$ decays to a) dimuons, and b) electron-positron pair.
Figure 3-9 The $\pi^+\pi^-$ invariant mass distribution for candidate $\gamma\mu\pi\pi$ events for the data set a) and b) and for the Monte Carlo samples c) and d).
Another important comparison between the data sample and the Monte Carlo is the distribution of \((\cos\theta)\), where \(\theta\) is the polar angle of the leptons in the rest frame of the \(\Psi\) with the \(z\) axis defined by the incident \(e^+e^-\) direction. The \((\cos\theta)\) distribution is shown in Figure 3-10 for both decay modes of the \(\Psi\). It can be seen qualitatively that both the data and the Monte Carlo are in good agreement, indicating that indeed the leptons are produced with a \((1 + \cos^2\theta)\) distribution.

### 3.6 Determining the Number of \(\Psi(3686)\)

To determine the number of radiative \((\Psi' \rightarrow \Psi \pi^+ \pi^-)\) events the \(\pi^+\pi^-\) recoil mass spectrum is fitted with two Gaussian functions and a second order Legendre polynomial of the form:

\[
f(m, \sigma_j, m_j, a_i) = \left( \frac{1}{\sigma_1^2} e^{-\frac{(m-m_1)^2}{2\sigma_1^2}} \right) + \left( \frac{\alpha}{\sigma_2^2} e^{-\frac{(m-m_2)^2}{2\sigma_2^2}} \right) + \sum_{i=1}^{2} a_i P_i(m) \quad \text{(EQ 3-2)}
\]

where \(m\) is the \(\pi^+\pi^-\) recoil mass, \(\sigma_j\) is the \(j\)th Gaussian width, with \((j = 1, 2)\), \(m_j\) is the \(j\)th Gaussian mean, \(a_i\) is the coefficient of the \(i\)th Legendre polynomial \(P_i\) \((i = 1, 2)\), and \(\alpha\) is the coefficient of the second Gaussian.

The fits are performed with BWGNEW, a Mark III fitting package based on CERN’s MINUIT fitting package.\(^{[46]}\)\(^{[47]}\) Since this package normalizes the fitting function automatically, the coefficient of the first term is arbitrary. The form of the polynomial function is chosen as a linear combination of Legendre polynomials because they are the natural form of polynomials used in this fitting package.

By fitting the \(\pi^+\pi^-\) recoil mass spectrum of the Monte Carlo events that have passed the various analysis stages described in previous sections, the number of \((\Psi' \rightarrow \Psi \pi^+ \pi^-)\) events and thus the overall detection efficiencies is calculated. The fitted \(\pi^+\pi^-\) recoil mass spectrum is shown for both channels in Figure 3-11 and Figure 3-12. The results along with the values of the fit parameters \(\sigma_j\) and \(m_j\) are shown in Table 3-3 for both decay chan-
Figure 3-10  $\cos\theta$ distribution for both the data set a) and b) and for Monte Carlo sample c) and d). The distributions agree with each other to a fair extent, indicating that the leptons are produced with a $(1 + \cos^2\theta)$ distribution in the rest frame of the $\Psi$. 
Figure 3-11 Fitted $\pi^+\pi^-$ recoil mass distribution of MC events where the $\Psi$ decays to a pair of muons.
Figure 3-12 Fitted $\pi^+\pi^-$ recoil mass distribution of MC events where the $\Psi$ decays to $e^+e^-$. 
nels of the \( \Psi \). The other parameters are not listed since they describe the flat background and are allowed to vary in subsequent fits.

### TABLE 3-3 The efficiency and fit parameters for \( \Psi_{\pi\pi} \) events.

<table>
<thead>
<tr>
<th>( \Psi ) Decay Mode</th>
<th>Efficiency</th>
<th>( m_1 ) (GeV)</th>
<th>( m_2 ) (GeV)</th>
<th>( \sigma_1 ) (MeV)</th>
<th>( \sigma_2 ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu\mu )</td>
<td>0.554±0.012</td>
<td>3.1000±0.0004</td>
<td>3.106±0.001</td>
<td>7.6±0.2</td>
<td>23.7±2.0</td>
</tr>
<tr>
<td>( ee )</td>
<td>0.509±0.015</td>
<td>3.1000±0.0002</td>
<td>3.105±0.001</td>
<td>7.7±0.2</td>
<td>21.0±2.0</td>
</tr>
</tbody>
</table>

In a similar fashion the number of \( (\Psi' \rightarrow \Psi \pi^+ \pi^-) \) events are obtained from the data sample which has passed the analysis criteria. However, when performing the fits to the \( \pi^+ \pi^- \) recoil mass spectrum, the values for the fit parameters \( \sigma_j \) and \( m_j \) are fixed at the values obtained from the Monte Carlo studies listed in the previous table. The other parameters describing the background combinatorics are allowed to vary since the flat combinatorics background is not present in the Monte Carlo generated data sets. The fitted \( \pi^+ \pi^- \) recoil mass spectrum is shown for both channels in Figure 3-13 and Figure 3-14. The results of the fits for the data sample is displayed in Table 3-4, where the second error is a systematic error indicating the spread of values obtained using other functional forms containing one Gaussian function and/or using only a first order or a third order polynomial to perform the fits:

### TABLE 3-4 Number of \( \Psi_{\pi\pi} \) events obtained from the fits for the two leptonic decay modes of the \( \Psi \).

<table>
<thead>
<tr>
<th>( \Psi ) Decay Mode</th>
<th>Number of Events Obtained from the Fits</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu\mu )</td>
<td>271±23±9</td>
</tr>
<tr>
<td>( ee )</td>
<td>254±30±55</td>
</tr>
</tbody>
</table>
Figure 3-13 Fitted $\pi^+\pi^-$ recoil mass distribution of events in the data sample, where the $\Psi$ decays to a pair of muons.
Figure 3.14 Fitted $\pi^+\pi^-$ recoil mass distribution of events in the data sample, where the $\Psi$ decays to $e^+e^-$. 
3.7 Results

Using the calculated values for the efficiencies and the branching ratios

\[ \text{BR} \left( \Psi' \rightarrow \Psi \pi^+ \pi^- \right) = (32.4 \pm 2.6)\% , \quad \text{BR} \left( \Psi' \rightarrow \mu^+ \mu^- \right) = (5.97 \pm 0.25)\% , \quad \text{and} \]

\[ \text{BR} \left( \Psi' \rightarrow e^+ e^- \right) = (6.27 \pm 0.20)\% , \]

the number of radiatively produced \( (\Psi'' \rightarrow \Psi \pi^+ \pi^-) \) events at \( \sqrt{s} = 3.77 \text{ GeV} \) are determined as indicated in Table 3-5.

<table>
<thead>
<tr>
<th>( \Psi ) Decay Mode</th>
<th>Number of ( \Psi'' ) Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu\mu )</td>
<td>25300\pm3000</td>
</tr>
<tr>
<td>( ee )</td>
<td>24600\pm4500</td>
</tr>
</tbody>
</table>

The systematic errors are combined in quadrature with the statistical errors in the above table. It is seen that the number of \( (\Psi'' \rightarrow \Psi \pi^+ \pi^-) \) events are in very good agreement using the two different decay channels of the \( \Psi \).

In the rest of this thesis the number obtained from the \( (\Psi' \rightarrow \mu^+ \mu^-) \) channel will be used to normalize the background due to the production of \( \Psi'' \)'s at \( \sqrt{s} = 3.77 \text{ GeV} \). The number from the \( (\Psi' \rightarrow e^+ e^-) \) channel is not used simply because the lepton identification depends only on the Mark III electromagnetic shower reconstruction in the shower counter through the calculation of \( (E/P) \), which is not very well understood. On the other hand the \( (\Psi' \rightarrow \mu^+ \mu^-) \) channel uses, in addition to the \( (E/P) \) measurement, the Muon system of Mark III, making it less sensitive to the shower reconstruction techniques.
Chapter 4

Four Pion Production

4.1 Introduction

The production of a particular final state by continuum $e^+e^-$ annihilation poses a potential source of background to decays of the $\Psi(3770)$. One method of estimating the contribution from the continuum is to look for the final states of interest among a data set collected at center of mass energies very close to the $\Psi(3770)$ mass region. However, in the absence of such a data sample, the data collected by Mark III at $\sqrt{s} = 4.14$ GeV will be used instead.

The idea is to find the number of events at $\sqrt{s} = 4.14$ GeV and then using a scale factor $f_s$, scale the number of events to the lower $\sqrt{s} = 3.77$ GeV. This will be taken as the contribution of the continuum production at $\sqrt{s} = 3.77$ GeV. As already mentioned in Chapter 1, the scale factor can be determined by assuming the scaling of inclusive hadron production in $e^+e^-$ annihilation in various scaling variables.

Another way to estimate the value of the scale factor $f_s$ is to use the Lund Monte Carlo, JETSET 6.2. In this method $f_s$ is simply the ratio of the number of Monte Carlo events at $\sqrt{s} = 3.77$ GeV to that at $\sqrt{s} = 4.14$ GeV. It is important to note that the absolute number of events produced by Lund is not used, rather the ratio of the number of events at two center of mass energies, which are only 370 MeV apart, is taken to arrive at a scale factor. It should also be pointed out that this technique is used only as a check of the scaling technique to provide some confidence in the results of the analysis.

As a test of the Lund method, this chapter presents the results of the analysis for the production of an exclusive hadronic channel, namely ($e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$). This particular final state with a +1 G-parity is chosen, since it cannot be produced by the hadronic decays of the $\Psi(3770)$, which has a -1 G-parity assignment. To be sure, electromagnetic decays of
the $\Psi(3770)$ to this final state is possible, but the contribution from this source is negligible, due to the small electronic width of the $\Psi(3770)$ (0.9 events are expected from this source at $\sqrt{s} = 3.77$ GeV).

4.2 General Event Selection

The search for $(e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-)$ events starts by requiring the events to have:

- four charged tracks,
- net charge of zero,
- $xy_{\text{vertex}} \leq 0.05$ m and $|z_{\text{vertex}}| \leq 0.1$ m
- each track satisfy a good helix fit and each track must have z information.

Where $xy_{\text{vertex}}$ and $z_{\text{vertex}}$ are the primary vertex positions in the xy plane and along the z-axis respectively. Table 4-1 shows the number of candidate events remaining after each of the above cuts are applied at $\sqrt{s} = 3.77$ GeV and at $\sqrt{s} = 4.14$ GeV for both the data set as well as for the Lund Monte Carlo, where all the events are scaled to an integrated luminosity of 9.0 pb$^{-1}$.

4.3 Particle Identification

Pions are identified by using either the time of flight (TOF) measurements or the dEdx measurements, provided they pass the requirements mentioned in Chapter 2 for using each of the particle identification subsystems such as polar angle cuts, quality cuts etc.

A track is said to be consistent with the pion hypothesis by the TOF method if $w_{t_{\pi}}$ (defined in Chapter 2) is greater than $6.0 \times 10^{-3}$, which was described in more detail in Chapter 2.

On the other hand if the dEdx system is used, a track is said to be consistent with the pion hypothesis if $-3.0 < \chi_{\pi} < 4.5$, where $\chi_{\pi}$ is defined as the difference in the values of the
measured and the predicted dE/dx in units of sigma, the dE/dx system resolution as described in Chapter 2.

To ensure high efficiency a very loose particle identification requirement is imposed on the events passing the general events selection mentioned above. Every track that has either time of flight information or dE/dx information is required to be consistent with the pion hypothesis. Table 4-1 shows the number of candidate events remaining for the various data sets after particle identification requirement is imposed.

4.4 Event Momentum, Energy, and Kinematic Fits to $\pi^+\pi^-\pi^+\pi^-$

After the particle identification requirements, the event’s total momentum and energy are calculated, where all the tracks are assumed to be charged pions. The distributions of these quantities are shown in Figure 4-1 and Figure 4-2 for both the data samples and the Monte Carlo samples. Similar distributions are shown in Figure 4-3 for Monte Carlo generated exclusive $\pi^+\pi^-\pi^+\pi^-$ events.

To select four pion final states, a 1-C kinematic fit to $\pi^+\pi^-\pi^+\pi^-$ hypothesis is performed. However, before fitting all the events remaining after the particle identification cuts, a very loose cut is imposed on the events total momentum and total energy:

- Event total momentum < 800 MeV/c,
- $(\sqrt{s} - 300)$ MeV < Event total energy < $(\sqrt{s} + 300)$ MeV

The aim of these requirements is two fold; The first goal is to reduce the number of events to be fitted, inorder to minimize the CPU usage, and the second goal is to keep the efficiencies high, which is why the cuts are kept so loose, as can be observed by looking at the distributions for Monte Carlo generated pure $\pi^+\pi^-\pi^+\pi^-$ events (see Figure 4-3).

After these general event momentum and energy cuts events are fitted kinematically to the four charged pion hypothesis to reject events with four charged pions that also contain one or more $\pi^0$’s. After a successful fit events with prob($\chi^2$) ≥ 0.01 are retained. The $\chi^2$ dis-
Figure 4-1 Event total momentum distribution for events passing the general event selection and particle identification requirements.
Figure 4-2 Event total energy distribution for events passing the general event selection and particle identification requirements.
Figure 4-3 Event momentum and energy distributions for Monte Carlo generated pure $\pi^+\pi^-\pi^+\pi^-$ events at the two center of mass energies.
tribution of events passing the fit is shown in Figure 4-4. Figure 4-5 and Figure 4-6 show the event total momentum and energy distributions for events passing the \( \textrm{prob}(\chi^2) \geq 0.01 \) cut.

Table 4-1 shows the number of candidate events remaining for the various data sets after these requirements and the ones mentioned in previous sections are imposed.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Data (3.77)</th>
<th>Data (4.14)</th>
<th>MC (3.77)</th>
<th>MC (4.14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four charged tracks</td>
<td>134013</td>
<td>76786</td>
<td>49397</td>
<td>38760</td>
</tr>
<tr>
<td>Net charge of zero</td>
<td>100447</td>
<td>57353</td>
<td>47618</td>
<td>37219</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>89119</td>
<td>50981</td>
<td>46881</td>
<td>36702</td>
</tr>
<tr>
<td>Track quality</td>
<td>80815</td>
<td>47517</td>
<td>44797</td>
<td>35134</td>
</tr>
<tr>
<td>Particle id</td>
<td>52876</td>
<td>29462</td>
<td>33363</td>
<td>25611</td>
</tr>
<tr>
<td>Event momentum</td>
<td>33192</td>
<td>16938</td>
<td>21239</td>
<td>13964</td>
</tr>
<tr>
<td>Event energy</td>
<td>3045</td>
<td>967</td>
<td>1997</td>
<td>916</td>
</tr>
<tr>
<td>Successful fit</td>
<td>1644</td>
<td>578</td>
<td>912</td>
<td>439</td>
</tr>
<tr>
<td>( \textrm{prob}(\chi^2) \geq 1% )</td>
<td>863</td>
<td>359</td>
<td>689</td>
<td>302</td>
</tr>
</tbody>
</table>

4.5 \( \Psi \pi^+\pi^- \) Background

One source of background that is expected to affect the data sample at \( \sqrt{s} = 3.77 \) GeV is the large production rate of radiatively produced \( \Psi' \), as discussed in the previous chapter, where the \( \Psi' \) decays through \( (\Psi' \to \Psi \pi^+ \pi^-) \) mode followed by the subsequent decay of the \( \Psi \) through either the \( (\Psi \to \mu^+ \mu^-) \) channel or the \( (\Psi \to e^+ e^-) \) channel. Since the radiated photon is expected to be fairly soft and since the particle identification for the detection of the four pion final state is kept very loose, this particular decay channel of the \( \Psi' \) is expected to contaminate the four pion event sample at \( \sqrt{s} = 3.77 \) GeV. The event
Figure 4-4 $\chi^2$ distribution for events passing the event momentum and energy requirements. The arrow corresponds to the 1% cut on $\text{prob}(\chi^2)$. 
Figure 4-5 Event total momentum distribution for events passing the (prob(χ²) > 1%) requirement.
Figure 4-6 Event total energy distribution for events passing the (prob($\chi^2$) > 1%) requirement.
sample at $\sqrt{s} = 4.14$ GeV is expected to be free of this source of background since the radiative $\Psi'$ production at this center of mass energy is fairly small. Two methods are explored to get an estimate of the background due to this source which are presented next.

4.5.1 Using the Radiative $\Psi'$ Production Monte Carlo

The four pion final state event selection criteria described in the previous sections is applied to radiatively produced $\Psi'$ Monte Carlo events. These are events that, as described in the previous chapter, decay the $\Psi'$ via ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) mode, and subsequently decay the $\Psi$ to either ($\Psi \rightarrow \mu^+ \mu^-$) or ($\Psi \rightarrow e^+ e^-$) final state.

After the four pion analysis criteria is applied, $(2.04 \pm 0.14)\%$ of ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) events, with the ($\Psi \rightarrow \mu^+ \mu^-$) decay mode and $(2.02 \pm 0.14)\%$ with the ($\Psi \rightarrow e^+ e^-$) decay mode are kept as $\pi^+ \pi^- \pi^+ \pi^-$ events. The event total momentum and energy distribution for these remaining events are shown in Figure 4-7. It is seen that these events look very much like genuine $\pi^+ \pi^- \pi^+ \pi^-$ events as can be compared with Figure 4-5 (a and c) and Figure 4-6 (a and c). Since the data sample at $\sqrt{s} = 3.77$ GeV contains $490 \pm 34$ ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) events in the ($\Psi \rightarrow \mu^+ \mu^-$) channel and $500 \pm 82$ events in the ($\Psi \rightarrow e^+ e^-$) channel (see the previous chapter where the detection efficiencies are discussed), 10.0 \pm 1.0 background events are expected from the ($\Psi \rightarrow \mu^+ \mu^-$) channel while 10.1 \pm 2.0 events from the ($\Psi \rightarrow e^+ e^-$) channel are expected. The total number of background events expected is therefore $20 \pm 2$.

4.5.2 Searching for $\gamma \Psi' \pi \pi$ events among the $\pi^+ \pi^- \pi^+ \pi^-$ candidates

Another method to estimate the background due to radiative ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) events is to search for these modes among the $\pi^+ \pi^- \pi^+ \pi^-$ sample obtained after all the four pion selection criteria is applied on the data sample. The search for ($\Psi' \rightarrow \Psi \pi^+ \pi^-$) events where the $\Psi$ decays to a pair of leptons is very similar to the one described in the previous chapter.

The $\pi^+ \pi^-$ recoil mass distribution for both the ($\Psi \rightarrow \mu^+ \mu^-$) and the ($\Psi \rightarrow e^+ e^-$) decay modes of the $\Psi$ is shown in Figure 4-8. After fitting these distributions with the
Figure 4-7 Event momentum and energy distribution for $\Psi\pi\pi$ events that pass the four pion event selection criteria for the two leptonic decay modes of the $\Psi$. 
Figure 4-8 $\pi^+\pi^-$ recoil mass distribution of events passing the four pion selection criteria for candidate events in the a) $\mu\mu$ and b) $ee$ decay channel of the $\Psi$. 
functional forms described in the previous chapter, while holding the values for the mean and the width of the Gaussians fixed to the Monte Carlo values (just as described in the fitting procedure of the previous chapter), 16±7 events are found in the \((\Psi \to \mu^+ \mu^-)\) channel and 19±10 events are found in the \((\Psi \to e^+ e^-)\) channel. The background is therefore estimated to be 35±12 events using this method.

It should be pointed out that no events were found in the data at \(\sqrt{s} = 4.14\) GeV or in the Lund Monte Carlo at \(\sqrt{s} = 3.77\) GeV and \(\sqrt{s} = 4.14\) GeV.

4.6 Results

After events are passed through the various selection criteria, the number of events remaining in the various data and Monte Carlo samples is shown in the last row of Table 4-1. However, as discussed in the previous section, the number of events in the data sample at \(\sqrt{s} = 3.77\) GeV must be corrected for contamination due to radiative \((\Psi' \to \Psi \pi^+ \pi^-)\) events. The contamination is estimated to be 28±12, the average of the values obtained using the two methods mentioned in the previous section.

The ratio of the number of events at the two center of mass energies,

\[
\text{Ratio} = \frac{N_{3.77}}{N_{4.14}}
\]  

(EQ 4-1)

is then calculated and is found to be 2.32±0.17 for the data sample and 2.28±0.23 using the Lund Monte Carlo. It is seen that the Lund Monte Carlo predicts very well the ratio of the number of events for an exclusive channel. It is hoped therefore that Lund can also predict the ratio of the number of events for an inclusive channel as well since it is generally thought to be an easier task than predicting the ratio for an exclusive channel. It should once again be pointed out that the Lund Monte Carlo is used only as a check to verify the results obtained using the scaling method.
Chapter 5

Inclusive Anti-proton Production

5.1 Introduction

As an example of Baryonic decays of the $\Psi(3770)$, this chapter will present the results of the anti-proton analysis. Searching for Baryonic, specifically anti-proton, decays of the $\Psi'$ has the advantage of not having any contamination from the decays of the D mesons, except for the case of mis-identification of tracks from D decays.

Since the majority of the protons are due to beam gas interactions, only anti-protons are considered in this analysis. It is assumed that the rate of decay of the $\Psi'$ to protons is the same as to the rate of decay to anti-protons. In what follows, the words proton and anti-proton are used interchangeably to mean anti-proton, unless specifically stated.

5.2 Event and Track Selection

Events are required to pass a “Good Event” criteria defined as a set of requirements on the value of the event primary vertex to reduce background events due to beam gas interactions and cosmics. The distribution of primary vertex position in the plane perpendicular to the beam axis and along the beam axis is shown below in Figure 5-1 for events that contain a proton using the Lund Monte Carlo. The values for the “Good Event” requirement cuts are also shown in these figures. The values for these cuts are kept loose enough as to not produce any major loss of our signal events:

- position in xy plane $\leq 0.05$ m
- $-0.1$ m $\leq$ position along z-axis $\leq 0.1$ m
Figure 5-1 Primary vertex position for events containing a proton using the Lund Monte Carlo. a) in the plane perpendicular to beam axis, b) along the beam axis. The arrows indicate the "Good Event" cut values imposed.
It can be seen that very few events are lost by imposing these cuts. The acceptance for this requirement, as calculated from the Lund Monte Carlo, is very high and independent of the proton momentum, as can be seen in Figure 5-2. It can be seen that up to a proton momentum of 1.2 GeV/c, which is the maximum proton momentum to which this analysis is sensitive (as will be discussed later), the acceptance due to this particular requirement is very high and flat. Nevertheless these effects are taken into account when we calculate the overall detection efficiencies.

Events are also required to have at least two charged tracks. The proton candidate track is further required to have a good helix fit as well as have z information.

### 5.3 Proton Reconstruction

Proton tracks are reconstructed in the drift chamber with high probability, if they have sufficient transverse momentum to reach at least the first three layer of the drift chamber, as already discussed in Chapter 2. Figure 5-3 shows the acceptance for proton track reconstruction as a function of proton momentum and its polar angle with respect to the beam axis. It is seen from this figure that the acceptance remains independent of the proton momentum above a value of around 0.3 GeV/c.

### 5.4 Proton Identification

Proton identification is accomplished by using the time of flight information only. Time of flight (TOF) information for a charged track is used if the track passes the requirements, such as polar angle cuts and quality cuts, mentioned in Chapter 2 for using the TOF system.
Figure 5-2 Acceptance for "Good Event" requirement as a function of proton momentum.
Figure 5-3 Proton reconstruction efficiency as a function of proton a) momentum, and b) polar angle with respect to the beam axis.
Protons are then identified by using two different algorithms. In the first method, the standard Mark III algorithm (also mentioned in Chapter 2), a track is identified as a proton by looking at the quantity

\[ wt_i \equiv \exp \left\{ -\frac{1}{2} \frac{(t - t_i)^2}{\sigma^2} \right\} \]  
(EQ 5-1)

where \( t \) is the measured time, and \( t_i \) is the predicted time for the particle hypothesis \( i \) (\( i = e, \pi, K, p \)). If the weight corresponding to the proton hypothesis (\( wt_p \)) is larger than that for any other hypothesis, and if \( wt_p > 4.0 \times 10^{-6} \), then the track is identified as a proton. This cut corresponds to a 3σ separation, as described in Chapter 2, for protons with a momentum up to about 1.2 GeV/c.

The efficiency for identifying protons as functions of proton momentum and proton polar angle with respect to the beam axis, is shown in Figure 5-4. The efficiency rises initially as the proton's momentum increases. This is basically because a proton must have at least 150 MeV/c of transverse momentum to reach the TOF system. As the proton’s momentum increases beyond 1.2 GeV/c \( (\beta = 0.8) \), the efficiency starts a slow decline. This comes about because at higher momenta particle identification by time of flight methods suffers from mis-identifications, in this case identifying a proton as a kaon (discussed later in this chapter).

In the second method the absolute residual time of flight \(|\Delta t_i|\) are calculated for the pion, kaon, and proton hypotheses. A track is identified as a proton if \(|\Delta t_p|\) is the smallest of the three absolute residuals, and in addition if \(|\Delta t_p| < 1.0 \text{ nsec}\). In Figure 5-5 the residuals for the kaon and proton hypotheses are plotted against each other for true proton (a) and true kaon (b) tracks generated by the Monte Carlo. The efficiency for identifying protons as functions of proton momentum and proton polar angle with respect to the beam axis is shown in Figure 5-6 using this algorithm.
Figure 5-4  Proton identification efficiency, using the weight method, as a function of a) proton momentum and b) proton polar angle.
Figure 5-5 Time of flight residuals for generated a) protons, and b) kaons. The residuals are shown in units of nsec.
Figure 5-6 Proton identification efficiency, using the TOF residual method, as a function of a) proton momentum and b) proton polar angle.
Comparing the efficiencies for the two identification algorithms, it is seen that the two methods are rather similar. For the rest of this analysis the first method for proton identification is used.

### 5.5 Calculating the Number of Protons from $\Psi''$ Decays

The distribution of anti-protons as functions of proton's momentum and the scaling variables $x_E$, $x', x_p$, $\xi$ are shown in Figure 5-7 for $\sqrt{s} = 3.77\, GeV$. The definition of these variables are stated in Chapter 1. To derive the branching fraction of $\Psi''$ to inclusive anti-protons various background subtractions must be performed and efficiency corrections must be applied. These corrections are discussed individually in the next sections. The number of anti-protons from the decays of the $\Psi''$ can then be obtained as follows:

\[
N = \frac{N_{3.77} - N_D - N_{\text{MisId}} - \left( N' \frac{\Psi'}{\text{data set}_\Psi} \right) N' - f_s \left( \frac{L_{3.77}}{L_{4.14}} \right) (n_{4.14} - n_{\text{MisId}})}{\varepsilon_{3.77}} - \frac{N_{4.14}}{\varepsilon_{4.14}}
\]  

(EQ 5-2)

with,

- $N_{3.77}$, $n_{4.14}$, and $N'$ = Number of anti-protons at $\sqrt{s} = 3.77\, GeV$, $\sqrt{s} = 4.14\, GeV$, and at $\Psi'$ energies, respectively.

- $N'_{\Psi'}$ = Number of $\Psi'$ at $\sqrt{s} = 3.77\, GeV$.

- $N_{\text{data set}_\Psi'}$ = Number of $\Psi'$ in $\Psi'$ data sample.

- $N_D$ is the number of anti-protons from D decays.

- $N_{\text{MisId}}$ and $n_{\text{MisId}}$ are the number of fake anti-protons at $\sqrt{s} = 3.77\, GeV$ and $\sqrt{s} = 4.14\, GeV$ respectively.

- $\varepsilon_{3.77}$, and $\varepsilon_{4.14}$ = Efficiency at $\sqrt{s} = 3.77\, GeV$, and $\sqrt{s} = 4.14\, GeV$ respectively.
Figure 5-7 Anti-proton distribution at $E_{CM} = 3.77$ GeV as a function of the particle's momentum and other scaling variables.
• $L_{3.77}$, and $L_{4.14}$ = Integrated luminosity at $\sqrt{s} = 3.77$ GeV , and $\sqrt{s} = 4.14$ GeV respectively.

• $f_s$ = Scale factor for scaling the number of events at $\sqrt{s} = 4.14$ GeV to the number of events at $\sqrt{s} = 3.77$ GeV.

It should be remembered that the number of anti-protons at various center of mass energies, and the efficiencies can be functions of the anti-proton momentum and other scaling variables.

5.6 Proton Detection Efficiencies

The overall efficiency for detecting protons is calculated as functions of proton’s momentum and the scaling variables $x_F$, $x'$, $x_P$ and $\xi$. The efficiency functions are shown in Figure 5-8 at $\sqrt{s} = 3.77 GeV$. The efficiencies are calculated using the Lund Monte Carlo JETSET 6.2. In order to minimize the model dependence of this analysis, the results are calculated for each bin of proton momentum as well as for each bin of the various scaling variables. It is seen that the efficiencies rise very rapidly up to a momentum value of around 0.3 GeV/c, reaching a value of about 65%. Since the efficiencies rise so rapidly below this momentum value, this analysis considers protons with momentum above 0.3 GeV/c. After reaching the maximum, the efficiency starts a slow decline. This is due to the fact that as the proton momentum increases the event multiplicity is lowered, causing a decrease in the event acceptance, since we require that at least two charged tracks be present in the volume of the detector. In this analysis protons are considered up to a momentum value of 1.2 GeV/c, after which the proton misidentification starts to become a factor, as will be discussed later in this chapter. It should be noted that even at this high momentum region the efficiency remains high at around 60%.

5.6.1 Efficiency Ratios at the Two Energies

In this analysis the data at $\sqrt{s} = 4.14 GeV$ is scaled down to $\sqrt{s} = 3.77 GeV$ to be used as a model for the continuum production, as will be discussed in detail in the next section.
Figure 5-8 Overall proton detection efficiency as a function of proton momentum, polar angle and various scaling variables.
However, before scaling, the data is corrected for efficiencies at their respective center of mass energies. The functions of interest are the ratios of the efficiencies at the two center of mass energies. These functions are shown in Figure 5-9 as functions of the scaling variables, as well as the proton momentum. As stated before, these functions are calculated using the Lund Monte Carlo. It is seen that the values for the ratios of the efficiencies are very much consistent with 1.0, and thus the efficiencies do not change very much between $\sqrt{s} = 4.14 GeV$ and $\sqrt{s} = 3.77 GeV$.

To study the dependence of these results on the specific features of the Lund model, these distributions of the ratios are calculated using various phase space models with fixed multiplicities. As an example of these studies Figure 5-10 shows the efficiency ratios for the case of phase space generated $\pi^+\pi^- p p$. In these phase space models the charged track multiplicities are fixed and the proton momentum distribution is different from the distributions obtained by using Lund. However, it is found that these ratios are very similar to the ratios calculated using the Lund model.

### 5.7 Backgrounds

A number of possible sources of backgrounds are studied and are subsequently subtracted from the data set. Each of these backgrounds is described separately in the next subsections.

#### 5.7.1 Decays of the $\psi(3686)$

The data at $\sqrt{s} = 3.77 GeV$ contain many $\psi'$, as discussed at length in Chapter 3. When calculating the $\psi''$ branching ratios, the yield due to the $\psi'$ decays must be subtracted. The anti-proton selection analysis is performed for the data taken at the $\psi'$ mass. The result is then scaled by the ratio of the number of $\psi'$ at $\sqrt{s} = 3.77 GeV$ to the number of $\psi'$ in the $\psi'$ data sample. This resulting distribution is then subtracted from the data.
Figure 5-9 Efficiency ratios at the two center of mass energies, 3.77 GeV and 4.14 GeV, as functions of proton momentum and the scaling variables.
Figure 5-10 Efficiency ratios at the two center of mass energies using a phase space model with fixed number of charged tracks.
5.7.2 Decays of D Mesons

Since the $\psi''$ decays primarily to a pair of D mesons, one must subtract the contribution of D decays to the anti-proton sample. In this analysis only particle misidentification causes trouble, since the D meson does not decay to anti-protons. Using the D model Monte Carlo of the Mark III, the contribution from misidentified tracks, mostly kaons, is very small, about 0.5%. This contamination is subtracted from the data.

5.7.3 Misidentified Tracks

Another source of background is the contamination due to misidentified tracks from continuum events. The probability of misidentification is derived from the Lund Monte Carlo. The Lund Monte Carlo is chosen over a single particle Monte Carlo, since the Lund Monte Carlo is more representative of hadronic continuum events. Figure 5-11 shows this probability as a function of the particle’s momentum. As can be seen the probability of mis-identifying tracks as protons is very small over a very broad range of momenta. Those tracks that are mis-identified as protons are mostly kaons. To determine the number of fake anti-protons, the mis-identification probability at each momentum bin is multiplied by the number of negatively charged tracks at that momentum bin. The distribution of the number of negatively charged tracks with momentum greater than 0.8 GeV/c for the data taken at $\sqrt{s} = 3.77 GeV$ is shown in Figure 5-12 as a function of their momentum. The 0.8 GeV/c momentum cutoff is chosen since below this momentum the misidentification probability is essentially nil. To calculate the contamination of the anti-proton sample in the data, the mis-identification probability as a function of momentum is multiplied by the number of negatively charged tracks at each of the momentum bins (see Figure 5-13). This product actually represents an upper bound on the number of fake anti-protons, since the mis-identification probability is multiplied by the total number of charged tracks at each momentum bin. The same procedure is used to estimate the contamination, due to mis-identified anti-protons, in the anti-proton sample at $\sqrt{s} = 4.14 GeV$. The contamination as a function of the track momentum is shown in Figure 5-14 below.
Figure 5-11 Probability of mis-identifying a charged track as a proton as a function of the charged track momentum.
Figure 5-12 Momentum distribution of negatively charged tracks at $E_{CM} = 3.77$ GeV. The distribution below 0.8 GeV/c is not shown because the mis-identification probability in that region is negligible.
Figure 5-13 Maximum number of fake anti-protons, due to TOF misidentification at $E_{CM} = 3.77$ GeV.
Figure 5-14 Maximum number of fake anti-protons, due to TOF misidentification at $E_{CM} = 4.14$ GeV.
It is seen that at the two center of mass energies the contribution from this source of background is fairly small below a proton momentum of 1.4 GeV/c. To be more conservative, this analysis searches for anti-protons up to a momentum value of around 1.2 GeV/c, at which point the contribution from this source is around 5% of the anti-proton yield at $\sqrt{s} = 3.77 \text{GeV}$. This background is also subtracted from the data.

### 5.7.4 Continuum Production

A major source of background is the contribution from the continuum $\text{e}^+\text{e}^-$ annihilation at $\sqrt{s} = 3.77 \text{GeV}$. This is subtracted by utilizing the data sample taken by Mark III at $\sqrt{s} = 4.14 \text{GeV}$. Two techniques are used to scale the results from $\sqrt{s} = 4.14 \text{GeV}$ down to $\sqrt{s} = 3.77 \text{GeV}$.

In the first method the continuum cross section at any center of mass energy, $s$, can be written to first order in $\alpha_s$ as

$$\sigma_{\text{continuum}} = \frac{\sigma_s(x)}{s} \left[ 1 + \frac{\alpha_s}{\pi} \right] \quad \text{(EQ 5-3)}$$

where $\sigma_s(x)$ is the $s$ independent part of the cross section, which can be a function of any scaling variable $x$. Since $\alpha_s$ varies logarithmically with $s$, for the purpose of this analysis which relates the cross sections at two center of mass energies only 370 MeV apart, the factor containing $\alpha_s$ can be absorbed in the $s$ independent part of the cross section. The inaccuracy introduced in this analysis due to this approximation is less than 0.5%.

The data at $\sqrt{s} = 4.14 \text{GeV}$ is then scaled down to $\sqrt{s} = 3.77 \text{GeV}$ after correcting for the $(1/s)$ dependence and the ratio of the integrated luminosities at the two center of mass energies.

The other technique for scaling the data at $\sqrt{s} = 4.14 \text{GeV}$ is to use Lund to predict the ratio of the number of anti-protons at the two center of mass energies. As we have seen in a Chapter 4, Lund predicts very well the ratio of the number of $\pi^+\pi^-\pi^+\pi^-$ events at the two center of mass energies. Predicting the correct number of events for an exclusive channel
is a difficult task for any model, such as Lund. However, since Lund predicts correctly the ratios of an exclusive channel, it is hoped that this model can predict the ratios of an inclusive channel, which can be considered a somewhat easier task than the exclusive case. The luminosity correction must still of course be applied to the data.

5.8 Results

After various background subtractions and efficiency corrections, the number of inclusive anti-protons from $\Psi''$ decays is calculated using Equation 5-2. As an example, Table 5-1 displays the contributions to the number of anti-protons from various sources along with the average efficiencies for anti-protons with $0.18 \leq x' \leq 0.72$. The notation is the same used in Equation 5-2. In trying to extract this number, two methods are used to scale the anti-proton yield at $\sqrt{s} = 4.14$ GeV down to $\sqrt{s} = 3.77$ GeV.

<table>
<thead>
<tr>
<th>$N_{3.77}$</th>
<th>$N_{4.14}$</th>
<th>$N'$</th>
<th>$N_D$</th>
<th>$N_{\text{MisI}d}$</th>
<th>$n_{\text{MisI}d}$</th>
<th>$\varepsilon_{3.77}$</th>
<th>$\varepsilon_{4.14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td>5460</td>
<td>2700</td>
<td>3300</td>
<td>36</td>
<td>60</td>
<td>35</td>
<td>0.63</td>
<td>0.63</td>
</tr>
</tbody>
</table>

**TABLE 5-1 Number of detected anti-protons from various sources along with the efficiencies at the two center of mass energies.**
5.8.1 The Scaling Variables

If scaling of the continuum production is assumed in any one of the chosen scaling variables, then the scale factor $f_s$ in Equation 6-3 becomes:

$$f_s = \frac{s_{4.14}}{s_{3.77}} = 1.21$$

(EQ 5-4)

where $s_{3.77}$ and $s_{4.14}$ are the square of the center of mass energies at 3.77 GeV and 4.14 GeV respectively. In this method the results are studied as functions of the appropriate scaling variable.

As an example, one scaling variable, namely $x'$, is chosen to present the methods of the analysis. At the end of this section the results of using the other scaling variables are also presented, which were obtained using similar techniques.

After performing the background subtraction and correcting for efficiencies the distribution for the number of anti-proton events as function of the anti-proton momentum and other scaling variables are shown in Figure 5-15.

The resulting number of events are displayed in the following table for each choice of the scaling variable.

<table>
<thead>
<tr>
<th>Scaling Variable</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x'$</td>
<td>86±710</td>
</tr>
<tr>
<td>$x_p$</td>
<td>84±705</td>
</tr>
<tr>
<td>$\xi$</td>
<td>88±720</td>
</tr>
</tbody>
</table>

The ratio of the number of events in the $\sqrt{s} = 3.77 GeV$ data set after the background subtraction to that in the $\sqrt{s} = 4.14 GeV$ data set is shown in Figure 5-16 below. In calculating this ratio, the data is not corrected for efficiencies since the efficiency functions do not alter very much at the two center of mass energies. It can be seen from
Figure 5-15  Anti-proton distributions as functions of scaling variables after performing the necessary background subtractions and efficiency corrections.
Figure 5.16  The ratio of the number of events at $E_{CM} = 3.77$ GeV after subtracting the backgrounds to that at $E_{CM} = 4.14$ GeV after background subtraction and scaling.
these plots that the ratios are very much consistent with 1.0, indicating the absence of any clear signal for anti-proton decays of the $\Psi''$.

It should be stressed that so far these results do not depend on any models, such as the Lund Monte Carlo. To check these results a comparison is made with the predictions of Lund, which is described in the next section.

### 5.8.2 Comparison With the Lund Monte Carlo

Since the Lund Monte Carlo is successful in predicting the correct scaling of the number of events in an exclusive channel, namely $\pi^+ \pi^- \pi^+ \pi^-$ (see Chapter 4), it is hoped that it will guide us in scaling the number of anti-protons from $\sqrt{s} = 4.14$ GeV to $\sqrt{s} = 3.77$ GeV. At $\sqrt{s} = 3.77$ GeV, Lund predicts 4900±100 inclusive anti-proton events with $0.18 < x' < 0.72$ (5460±75 events are seen in the data), while 4500±100 events are predicted at $\sqrt{s} = 4.14$ GeV in the same $x'$ interval (3860±350 events are seen in the data after correcting for the relative integrated luminosities at the two center of mass energies).

The data at $\sqrt{s} = 4.14$ GeV is then scaled using the scale factor $f_s$ of Equation 7-3, where

$$f_s = \frac{n_{3.77}}{n_{4.14}} = 1.11 \pm 0.03$$  \hspace{1cm} (EQ 5-5)

Here $n_{3.77}$ and $n_{4.14}$ denote the number of anti-proton events at the respective center of mass energies. Using this scale factor, one obtains $720\pm600 \, \Psi''$ events decaying inclusively to anti-protons.

### 5.8.3 Determining the Branching Fraction

Since $(\Psi'' \rightarrow p + X)$ is not observed, upper limits can be placed on the decay. However, the cross section for $\Psi''$ production is not very well known. It is therefore more useful to place an upper limit on the product of the $\Psi''$ cross section and the branching fraction to
anti-protons. Using the results from the scaling studies the following upper limit is placed with a 90% CL:

\[ \sigma \cdot B \leq 0.24 \text{ nb} \]

Here it is assumed that the rate of proton production is equal to the rate of anti-proton production.

The second method of scaling, which uses Lund to predict the scale factor, places the following upper limit at 90% CL:

\[ \sigma \cdot B \leq 0.35 \text{ nb} \]

The following table lists the upper limits on the branching ratio and on the partial widths of the \((\Psi'' \rightarrow p + X)\), using certain values for the production cross section of the \(\Psi''\).

<table>
<thead>
<tr>
<th>(\sigma_{\Psi''} ) (nb)</th>
<th>BR ((\Psi'' \rightarrow p + X)) (\times 10^{-3})</th>
<th>(\Gamma (\Psi'' \rightarrow p + X)) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>48.0</td>
<td>1130.</td>
</tr>
<tr>
<td>9.3</td>
<td>26.0</td>
<td>610.</td>
</tr>
</tbody>
</table>
Chapter 6

Inclusive Λ Production

6.1 Introduction

As a second example of Baryonic decays of the ψ(3770), the results of the inclusive \( \bar{\Lambda} \) analysis will be presented in this chapter. This analysis mode has the distinct advantage, as did the anti-proton mode, of not having any contamination from the decays of the D mesons, aside from mis-identified tracks from the decays of the D mesons, which is small but will be accounted for as will be described later in this chapter.

\( \bar{\Lambda} \)'s are reconstructed through their decay channel \( (\bar{\Lambda} \rightarrow \bar{p} + \pi^+) \). As in the case of the anti-proton analysis, only \( \bar{\Lambda} \)'s are considered, since the majority of the protons are produced in beam gas interactions making the \( (\Lambda \rightarrow p + \pi^-) \) channel hard to detect simply for combinatorics reasons. In what follows, the \( \Lambda \) and \( \bar{\Lambda} \) are used interchangeably to mean \( \bar{\Lambda} \), unless specifically stated.

6.2 \( \bar{\Lambda} \) Reconstruction

As mentioned above \( \bar{\Lambda} \)'s are reconstructed through their decay channel \( (\bar{\Lambda} \rightarrow \bar{p} + \pi^+) \). The advantages of this decay channel are obvious, namely a rather large branching fraction \( (64.1 \pm 0.5) \% \), as well as charged decay products.

6.2.1 Event and Track Selection

Events are required to pass the "Good Event" criteria, which were discussed in the previous chapter. This requirement which simply imposes a cut on the position of the event primary vertex is used to reduce background events due to beam gas interactions and
cosmics. The distribution of primary vertex position in the plane perpendicular to the beam axis and along the beam axis is shown below in Figure 6-1 for events that contain a \( \Lambda \) using the Lund Monte Carlo. The values for the "Good Event" requirement cuts are also shown in these figures. The values for these cuts are kept loose enough as to not produce any major loss of our signal events:

- position in xy plane \( \leq 0.05 \) m
- \(-0.1 \) m \( \leq \) position along z-axis \( \leq 0.1 \) m

It can be seen that very few events are lost by imposing these cuts. The acceptance for this requirement, as calculated from the Lund Monte Carlo, is very high and independent of \( \Lambda \) momentum, as can be seen in this Figure 6-2. The slight decrease of acceptance at higher momenta is due to the fact that at higher momenta the \( \Lambda \) decay length increases, resulting in primary vertices that are further away from the interaction point (IP). It can be seen that up to a \( \Lambda \) momentum of 1.2 GeV/c, which is the maximum \( \Lambda \) momentum at which this analysis is sensitive (as will be discussed later), the acceptance due to this particular requirement is very high and flat. Nevertheless these effects are taken into account when we calculate the overall detection efficiencies.

Events are also required to have at least two charged tracks. The proton and pion candidate tracks are further required to have a good helix fit as well as have z information.

### 6.2.2 Proton and Pion Track Reconstruction

The \( \Lambda \) decays to a proton and a charged pion with a branching fraction of \( (64.1 \pm 0.5) \% \). The momentum of the proton and the pion is 101 MeV/c in the \( \Lambda \) rest frame. Since protons are much more massive than pions, most of the \( \Lambda \)'s momentum in the lab frame is carried out by the proton. The pion momentum spectrum is sharply peaked at very low momenta and falls off steadily to about 400 MeV/c. In fact even for a \( \Lambda \) with a momentum of 1.6 GeV/c, the maximum momentum that the daughter pion track can have is about 420 MeV/c. This effect as well as the generated momentum distributions of the \( \Lambda \) and the
Figure 6-1 Primary vertex position for $\Lambda$ events using the Lund Monte Carlo.

a) in plane perpendicular to beam axis, b) along the beam axis. The arrows indicate the "Good Event" cut values imposed.
Figure 6-2 Acceptance for “Good Event” requirement as function of $\Lambda$ momentum.
daughter proton track is shown below in Figure 6-3 based on the Lund Monte Carlo prediction.

6.2.2.1 Proton Reconstruction

Protons must have a transverse momentum of at least 120 MeV/c to be reconstructed. The other main feature of proton reconstruction efficiency, as can be seen from Figure 6-4, is its decrease as the Λ momentum increases. This is due to the fact that as the Λ momentum increases, its decay length also increases, as can be seen in Figure 6-5. Once the decay length in the plane perpendicular to the beam axis (d_{xy}) is beyond the first layer of the drift chamber, which is at a radius of 13.4 cm, the track reconstruction efficiency is very low (see Chapter 2 which describes the Mark III experiment). This effect can be seen in Figure 6-6 where a cut on proton transverse momentum is imposed to isolate the efficiency loss due to low proton P_T. This function looks very much like a step function with an average value of about 96% for d_{xy} less than 14 cm, and going down to zero for d_{xy} over 14 cm. Using this simplified model for the efficiency function along with the decay length probability as a function Λ momentum, one can predict the efficiency function as a function of Λ momentum. This prediction, along with the “true” efficiency as a function of Λ momentum is shown in Figure 6-7. These two functions are very similar indicating that the decrease in the efficiency as Λ’s momentum increases is really due to the increasing Λ decay length, resulting into Λ’s decaying well inside the drift chamber, thus reducing the chance of observing the daughter tracks.

6.2.2.2 Pion Reconstruction

The primary feature of the pion reconstruction efficiency is the loss of low momentum pions. These very low momenta pions curl around in the drift chamber and in the process do not get reconstructed. Figure 6-8 shows the pion reconstruction efficiency as a function the pion transverse momentum. At the high end of the pion momentum spectrum, the efficiency becomes flat at a value above 90%. It should, however, be noted that this efficiency is calculated assuming the sister proton track is already reconstructed. In doing so the effect of Λ decay length increase as a function of Λ momentum is taken out.
Figure 6-3 Momentum spectrum of $\Lambda$, and its decay products proton, and pion as predicted by the Lund Monte Carlo. Pions tend to have very low momenta. The arrow indicates two body $\Lambda\bar{\Lambda}$ production.
Figure 6-4 Proton reconstruction efficiency as a function of a) $\Lambda$ momentum and b) proton transverse momentum with respect to the beam axis.
Figure 6-5  Probability that a $\Lambda$ particle travels a distance $x$ or greater before decaying. This probability function is shown for different momentum bins.
Figure 6-6 Proton reconstruction efficiency, for protons with $P_T > 0.25 \text{ GeV/c}$ as a function of lambda decay length.
Figure 6-7  a) Predicted and b) “true” efficiency for reconstructing protons as a function of Λ momentum. The prediction used a simple model of the efficiency as a function of the Λ decay length.
Figure 6-8  Pion reconstruction efficiency as a function of the pion transverse momentum.
6.3 Proton Identification

Protons are identified by using the time of flight (TOF) information only, using the standard Mark III algorithm discussed in Chapter 2 and used in the inclusive anti-proton search (Chapter 5). Time of flight (TOF) information for a charged track is used if the track passes the requirements, such as polar angle cuts and quality cuts, mentioned in Chapter 2 for using the TOF system. A track is said to be a proton if it is identified as a “definite proton”, defined in Chapter 5.

The efficiency for identifying protons as functions of proton momentum and proton polar angle with respect to the beam axis, is shown in Figure 6-9. The efficiency rises as the proton’s momentum increases. This is basically because a proton must have at least 150 MeV/c of transverse momentum to reach the TOF system. As the proton’s momentum increases beyond 1.2 GeV/c ($\beta = 0.8$), the efficiency starts a slow decline. This comes about because at higher momenta particle identification by time of flight methods suffers from mis-identifications, in this case identifying a proton as a kaon, as discussed in the last chapter.

6.4 $\bar{\Lambda}$ Reconstruction

After requiring events to pass the event selection cuts, $\Lambda$’s are reconstructed by combining a negatively charged proton candidate with a positively charged pion which can be any positive charged track. Both the anti-proton and the pion tracks are required to pass the track selection cuts discussed above.

Once the two oppositely charged tracks are combined their invariant mass is formed. Figure 6-10 below shows this mass spectrum for both the data and the Lund Monte Carlo at $\sqrt{s} = 3.77$ GeV. Also shown in this figure is the mass spectrum for a combination of an anti-proton candidate track with a negatively charged pion, the so-called “wrong sign” combination. It can be seen that in this case no signal is seen in the $\Lambda$ mass region.
Figure 6-9  Proton identification efficiency as a function of a) proton momentum, and b) proton polar angle.
Figure 6-10 Invariant mass distribution of an anti-proton and a charged pion candidate. a) and b) are calculated from data, while c) and d) are obtained from Lund. c) and d) show the so called “wrong sign” or “wrong mass” combination.
The distribution of candidate $\Lambda$'s with a proton-pion invariant mass in the [1.10,1.13] GeV/c**2 range as functions of $\Lambda$'s momentum and the scaling variables $x_E$, $x'$, $x_P$, $\xi$ are plotted in Figure 6-11 for $\sqrt{s} = 3.77 GeV$.

### 6.5 Calculating the Number of $\Lambda$'s from $\Psi''$ Decays

To determine the number of $\Psi''$ decaying inclusively to $\Lambda$'s, the $\Lambda$ yields from radiatively produced $\Psi'$ as well as the yields from $\sqrt{s} = 4.14$ GeV must be subtracted from the number of $\Lambda$'s obtained at $\sqrt{s} = 3.77$ GeV. As discussed fully in the previous chapter the subtractions must be corrected for integrated luminosity and efficiency differences. The subtraction at $\sqrt{s} = 4.14$ GeV must also be corrected by an appropriate scale factor. To be specific, the number of $\Psi''$ decaying inclusively to $\Lambda$'s is obtained as follows:

$$N = \frac{N_{3.77} - \left( \frac{N_{3.77}^{\Psi'}}{N_{\text{data set}}^{\Psi'}} \right) N'}{e_{3.77}} - \frac{f_s \left( \frac{L_{3.77}}{L_{4.14}} \right) N_{4.14}}{e_{4.14}}$$  \hspace{1cm} (EQ 6-1)

with,

- $N_{3.77}$, $N_{4.14}$, and $N'$ = Number of $\Lambda$'s at $\sqrt{s} = 3.77$ GeV, $\sqrt{s} = 4.14$ GeV, and at $\Psi'$ energies, respectively.

- $N_{3.77}^{\Psi'}$ = Number of $\Psi'$ at $\sqrt{s} = 3.77$ GeV.

- $N_{\text{data set}}^{\Psi'}$ = Number of $\Psi'$ in $\Psi'$ data sample.

- $e_{3.77}$, and $e_{4.14}$ = Efficiency at $\sqrt{s} = 3.77$ GeV, and $\sqrt{s} = 4.14$ GeV respectively.

- $L_{3.77}$, and $L_{4.14}$ = Integrated luminosity at $\sqrt{s} = 3.77$ GeV, and $\sqrt{s} = 4.14$ GeV respectively.

- $f_s =$ Scale factor for scaling the number of events at $\sqrt{s} = 4.14$ GeV to the number of events at $\sqrt{s} = 3.77$ GeV.
Figure 6-11  Momentum and scaling variable distributions for candidate Λ’s with a proton-pion invariant mass in the [1.10,1.13] GeV/c**2 range for the data sample at $E_{CM} = 3.77$ GeV.
After obtaining $N$, a correction factor $C_f$ is applied to arrive at the number of $\Psi''$ decaying inclusively to $\Lambda$'s. This correction factor, which will be explained in more detail later, compensates for the loss of $\Lambda$'s in the tails of the proton-pion invariant mass fits.

It should be remembered that as in the anti-proton analysis, the number of $\Lambda$'s at various center of mass energies, the efficiencies, and $C_f$ can be functions of the $\Lambda$ momentum and other scaling variables.

### 6.6 Overall $\Lambda$ Detection Efficiency

The proton-pion invariant mass distribution for generated $\Lambda$'s as calculated from Monte Carlo is shown below (see Figure 6-12). It can be seen that true Monte Carlo generated $\Lambda$'s have broad tails in this invariant mass spectrum. The effect of this tail must be taken into account as well be discussed later in this chapter. Noting this tail in the distribution, a combination of anti-proton and positively charged pion candidates is accepted as a possible $\Lambda$ if their invariant mass distribution is less than $1.16$ GeV/c$^2$. This will be the cut used in calculating the efficiency for reconstructing a $\Lambda$. It should be pointed out that not every anti-proton pion candidate combination with an invariant mass of less than $1.16$ GeV/c$^2$ is a $\Lambda$. The number of $\Lambda$'s is determined from performing fits to the invariant mass distribution, which is discussed later in this chapter.

The overall efficiency for detecting $\Lambda$'s as functions of $\Lambda$ momentum and various scaling variables, is depicted in Figure 6-13. The efficiency does not include the branching ratio of $(\Lambda \rightarrow p + \pi^-)$. It is seen that the efficiencies rise very rapidly up to a momentum value of around $0.5$ GeV/c, to a value of about $40\%$. Since the efficiencies rise so rapidly below this momentum value, this analysis considers $\Lambda$'s with momentum above $0.5$ GeV/c. Above this cutoff the efficiency remains flat up to a momentum value of $1.2$ GeV/c, after which the efficiency slowly decreases due to the increasing $\Lambda$ decay length. Above a momentum of $1.2$ GeV/c the errors on the efficiencies start to increase. Therefore in this analysis $\Lambda$ candidates are considered if its momentum is less than $1.2$ GeV/c.
Figure 6-12 Invariant mass distribution for Monte Carlo generated Λ's.
Figure 6-13 Overall $\Lambda$ detection efficiency as a function of $\Lambda$ momentum and various scaling variables.
6.6.1 Efficiency Ratios at the Two Center of Mass Energies

The importance of the efficiency ratios at the two center of mass energies, $\sqrt{s} = 3.77$ GeV and 4.14 GeV, has already been discussed in the inclusive anti-proton production chapter (Chapter 5). These ratios for $\Lambda$ efficiencies have also been calculated as functions of the various scaling variables. These ratios are very much consistent with 1.0 above a $\Lambda$ momentum of 0.5 GeV/c. As an example, Figure 6-14 shows these ratios as functions the $\Lambda$ momentum and $x'$.

6.7 Determining the Number of $\Lambda$'s

The number of $\Lambda$'s are determined by fitting the candidate anti-proton pion invariant mass plots with a Gaussian along with an exponential factor and a second order polynomial. This function is shown below,

$$f(m, c_1) = [1 + c_1 m + c_2 m] [1 - \alpha e^{-\beta (m + 1)}] + \left[ \frac{c_3}{\sigma \sqrt{2\pi}} e^{-\frac{(m - m_{\Lambda})^2}{2\sigma^2}} \right]$$

(EQ 6-2)

where $m$ is the proton-pion invariant mass, and $c_1 = \{ c_1, c_2, c_3, \alpha, \beta, m_{\Lambda}, \sigma \}$ are the parameters of the fit. The polynomial in the first term with coefficients $c_1$, and $c_2$ describes the background, while the Gaussian term with coefficient $c_3$, mean $m_{\Lambda}$ and width $\sigma$ describes the signal. The exponential function with parameters $\alpha$ and $\beta$ describes the abrupt rise of the invariant mass spectrum at the proton-pion mass. A typical fit is shown in Figure 6-15.

The mass spectrum is divided into bins of the chosen scaling variable. The Gaussian width $\sigma$ along with the $\Lambda$ mass $m_{\Lambda}$ are determined by fitting the invariant mass spectrum obtained from the Lund Monte Carlo. Then the mass spectrum from the data sets are fit to this hypothesis, holding $\sigma$ and $m_{\Lambda}$ fixed at the values obtained from the Monte Carlo fits. The number of $\Lambda$'s are then determined by obtaining the area under the Gaussian peak. The values of the width for the various $x'$ bins are shown in Figure 6-16 below. It is seen that $\sigma$ is fairly independent of the scaling variable.
Figure 6-14 Efficiency ratios at the two center of mass energies, 3.77 GeV and 4.14 GeV, as functions of $\Lambda$ momentum and $x'$.
Figure 6-15  A typical fit of the anti-proton pion invariant mass spectrum.
Figure 6-16  The Gaussian widths determined from the Monte Carlo, for different $x'$ bins.
A minor correction to the number of $\Lambda$'s are made due to the long tails of the true $\Lambda$ mass spectrum, which was mentioned earlier. When the mass spectrum from the Monte Carlo is fitted, the number of $\Lambda$'s can be extracted from this fit. This number can then be compared with the actual number of $\Lambda$'s reconstructed in that specific scaling variable bin. The ratio of these two numbers gives the correction factor, with which the results of the fits are corrected. Figure 6-17 shows the values of this correction for different $x'$ bins. It is seen that the correction is not only small, but also independent of the scaling variable $x'$. This independence is also observed for other choices of the scaling variables. After performing a similar exercise at $\sqrt{s} = 4.14$ GeV and at $\Psi'$ energies, it is determined that this correction factor is independent of the center of mass energies. The average value of this correction factor, $C_f$ is estimated to be $1.137 \pm 0.018$.

6.8 Results

To determine the number of $\Psi''$ decaying inclusively to $\Lambda$'s, the $\Lambda$ yields from radiatively produced $\Psi'$ as well as the yields from $\sqrt{s} = 4.14$ GeV must be subtracted from the number of $\Lambda$'s obtained at $\sqrt{s} = 3.77$ GeV. As stated in Equation 6-1, the subtractions must be corrected for integrated luminosity and efficiency differences. The subtraction at $\sqrt{s} = 4.14$ GeV must also be corrected by an appropriate scale factor.

As an example, Table 6-1 displays the contributions to the number of $\bar{\Lambda}$'s from various sources along with the average efficiencies for $\Lambda$ with $0.33 \leq x' \leq 0.92$. The notation is the same used in Equation 6-1.

<table>
<thead>
<tr>
<th>TABLE 6-1</th>
<th>Number of detected $\bar{\Lambda}$'s from various sources along with the efficiencies at the two center of mass energies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{3.77}$</td>
<td>375$\pm$22</td>
</tr>
<tr>
<td>$N_{4.14}$</td>
<td>156$\pm$15</td>
</tr>
<tr>
<td>$\bar{N}'$</td>
<td>323$\pm$21</td>
</tr>
<tr>
<td>$\epsilon_{3.77}$</td>
<td>0.390$\pm$0.007</td>
</tr>
<tr>
<td>$\epsilon_{4.14}$</td>
<td>0.375$\pm$0.011</td>
</tr>
</tbody>
</table>
Figure 6.17 Mass fit correction factor for various $x'$ bins.
After obtaining \( N \), the correction factor \( C_f \) is applied to arrive at the number of \( \Psi'' \) decaying inclusively to \( \Lambda' \)'s. It should be remembered that as in the anti-proton analysis, the number of \( \Lambda' \)'s at various center of mass energies, the efficiencies, and \( C_f \) can be functions of the \( \Lambda \) momentum and other scaling variables.

In trying to extract the number of \( \Psi'' \) decaying inclusively to \( \Lambda' \)'s, two methods are used to scale the \( \Lambda \) yield at \( \sqrt{s} = 4.14 \text{ GeV} \) down to \( \sqrt{s} = 3.77 \text{ GeV} \), just as in the anti-proton analysis.

### 6.8.1 The Scaling Variables

If scaling of the continuum production is assumed in any one of the chosen scaling variables, then the scale factor \( f_s \) in Equation 6-1 becomes:

\[
f_s = \frac{s_{4.14}}{s_{3.77}} = 1.21 \tag{EQ 6-3}
\]

where \( s_{3.77} \) and \( s_{4.14} \) are the square of the center of mass energies at 3.77 GeV and 4.14 GeV respectively. In this method the results are studied as functions of the appropriate scaling variable.

As an example, one scaling variable, namely \( x' \), is chosen to present the methods of the analysis. At the end of this section the results of using the other scaling variables are also presented, which were obtained using similar techniques.

The number of \( \Psi'' \) decaying inclusively to \( \Lambda' \)'s as a function of the scaling variable \( x' \) is shown in Figure 6-18 both with and without the mass fit correction factor. The variable \( x' \) is chosen only as an example. The results as functions of the other scaling variables are similar. It can be seen, from this figure, that there is no evidence for the inclusive decay of \( \Psi'' \) to \( \Lambda' \)'s. The ratio of the number of events in the \( \sqrt{s} = 3.77 \text{ GeV} \) data set, after correcting for the \( \Psi' \) contribution, to that in the \( \sqrt{s} = 4.14 \text{ GeV} \) data set as functions of various scaling variables, also show no evidence for \( \Psi'' \) decays to \( \Lambda' \)'s. This result is shown for one of the scaling variables, \( x' \), in Figure 6-19. These distributions of ratios have the advant-
Figure 6-18 Number of $\Lambda$ events after background subtractions, and efficiency corrections a) without and b) with the mass fit correction.
Figure 6-19 Ratio of inclusive $\Lambda$ events at $\sqrt{s} = 3.77$ GeV and $\sqrt{s} = 4.14$ GeV, after subtracting the radiative $\Upsilon'$ contribution.
tage of having a very weak dependence on the values of efficiencies, since the efficiency ratios are very close to unity as discussed earlier. The net number of $\Psi^{'}$ decaying inclusively to $\Lambda$'s is shown in the table for the various choices of the scaling variables. It

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Scaling Variable & Number of Events \\
\hline
$\chi_E$ & $80 \pm 129$ \\
\hline
$\chi_P$ & $78 \pm 129$ \\
\hline
$\chi'$ & $76 \pm 132$ \\
\hline
$\xi$ & $80 \pm 131$ \\
\hline
\end{tabular}
\caption{Number of $\Psi^{'}$ decaying inclusively to $\Lambda$'s}
\end{table}

should be stressed that sofar these results do not depend on any models, such as the Lund Monte Carlo. To check these results a comparison is made with the predictions of Lund, which is described in the next section.

6.8.2 Comparison With the Lund Monte Carlo

Since the Lund Monte Carlo is successful in predicting the correct scaling of the number of events in an exclusive channel, namely $\pi^+ \pi^- \pi^+ \pi^-$ (see Chapter 4), it is hoped, just as in the anti-proton analysis, that it will guide us in scaling the number of $\Lambda$'s from $\sqrt{s} = 4.14$ GeV to $\sqrt{s} = 3.77$ GeV. At $\sqrt{s} = 3.77$ GeV, Lund predicts $790 \pm 40$ inclusive $\Lambda$ events with $0.33 < \chi' < 0.92$ (375$\pm$22 events are seen in the data), while 710$\pm$40 events are predicted at $\sqrt{s} = 4.14$ GeV in the same $\chi'$ interval (223$\pm$30 events are seen in the data at this center of mass energy). The data at $\sqrt{s} = 4.14$ GeV is then scaled using the scale factor $f_s$ of Equation 7-3, where

$$f_s = \frac{n_{3.77}}{n_{4.14}} = 1.12 \pm 0.08$$

(EQ 6-4)

Here $n_{3.77}$ and $n_{4.14}$ denote the number of $\Lambda$ events at the respective center of mass energies. Using this scale factor, one obtains $126 \pm 118$ $\Psi^{'}$ events decaying inclusively to $\Lambda$'s.
After applying the average correction factor, \( C_b \), the number of \( \Lambda \) events becomes 143\pm134.

### 6.8.3 Determining the Branching Fraction

Since \( (\Psi'' \rightarrow \Lambda + X) \) is not observed, upper limits can be placed on the decay. However, the cross section for \( \Psi'' \) production is not very well known. It is therefore more useful to place an upper limit on the product of the \( \Psi' \) cross section and the branching fraction to \( \Lambda \)'s. Using the results from the scaling studies the following upper limit is placed with a 90\% CL:

\[
\sigma \cdot B \leq 0.058 \text{ nb}
\]

Here it is assumed that the rate of \( \Lambda \) production is equal to the rate of \( \bar{\Lambda} \) production.

The second method of scaling, which uses Lund to predict the scale factor, places the following upper limit at 90\% CL:

\[
\sigma \cdot B \leq 0.074 \text{ nb}
\]

The following table lists the upper limits on the branching ratio and on the partial widths.

<table>
<thead>
<tr>
<th>( \sigma_{\Psi''} ) (nb)</th>
<th>( \text{BR} (\Psi'' \rightarrow \Lambda + X) \times 10^{-3} )</th>
<th>( \Gamma (\Psi'' \rightarrow \Lambda + X) ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>11.6</td>
<td>274.</td>
</tr>
<tr>
<td>9.3</td>
<td>6.2</td>
<td>146.</td>
</tr>
</tbody>
</table>

The following table lists the upper limits on the branching ratio and on the partial widths of the \( (\Psi'' \rightarrow \Lambda + X) \), using two different values for the production cross section of the \( \Psi'' \).
Chapter 7

Inclusive $\phi$ Production

7.1 Introduction

As another example of inclusive hadronic decays of the $\Psi(3770)$, inclusive $\phi$ production will be studied in this chapter. The main differing feature of this analysis, as compared with the previous inclusive analyses of $\bar{p}$ and $\bar{\Lambda}$ production, is the presence of background due to the decays of the $D$ mesons. The techniques for subtracting this source of contamination will be discussed fully later in this chapter.

7.2 Event and Track Selection

To reduce the background due to beam gas interactions and cosmics, events are required to pass the “Good Event” criteria, discussed in the anti-proton analysis chapter (Chapter 5). This requirement simply imposes a cut on the value of the event primary vertex. The distribution of primary vertex position in the plane perpendicular to the beam axis and along the beam axis is shown below in Figure 7-1 for events containing a $\phi$ using the Lund Monte Carlo. The values for the “Good Event” requirement cuts are indicated by arrows in these figures. The values for these cuts are kept loose enough as to not produce any major loss of signal events. The acceptance for this requirement, as calculated from the Lund Monte Carlo is about 98%.

Events are also required to have at least two charged tracks. The two kaon candidate tracks are further required to have a good helix fit as well as have $z$ information.
Figure 7-1 Primary vertex position for φ events using the Lund Monte Carlo. a) in the plane perpendicular to the beam axis, b) along the beam axis. The arrows indicate the “Good Event” cuts.
7.3 Reconstructing $\phi$ daughter tracks

$\phi$'s are reconstructed through their decay channel ($\phi \rightarrow K^+K^-$). Reconstructing $\phi$'s through this channel has the advantage of having a rather large branching ratio $(49.1 \pm 0.8)\%$, as well as having only charged decay products.

Kaons have a momentum of 127 MeV/c in the $\phi$ rest frame. The momentum spectrum of kaons, coming from decays of the $\phi$ mesons, as predicted by the Lund Monte Carlo is shown in Figure 7-2. The generated momentum distribution of the $\phi$ mesons is also shown in the figure.

Kaons are reconstructed provided that they possess a transverse momentum of 120 MeV/c or more. Figure 7-3 shows the individual kaon reconstruction efficiency as a function of the kaon momentum as well as its transverse momentum. This includes the effects of kaons decaying well inside the drift chamber, and thus not getting reconstructed. For kaons that do not decay the reconstruction efficiency is much higher as can be seen in the same figure.

The average reconstruction efficiency is about 80\% in the kaon momentum interval $[0.25,0.95]$ GeV/c. When kaons are not allowed to decay the average reconstruction efficiency reaches to about 93\% in the same momentum interval. As mentioned in a previous chapter describing the Mark III detector, good tracking efficiency is achieved for tracks which reach layer 3 of the drift chamber which extends to a radius of 0.53 m. Therefore if a kaon reaches the end of layer 3, then it has a high probability of getting reconstructed. The calculated probability that a kaon decays before reaching the end of layer 3 is given by:

$$\text{Probability} = 1 - \exp\left(-\frac{Mx_0}{p c \tau}\right)$$

where $M$ is the kaon mass, $p$ is its momentum and $\tau$ is its mean lifetime, $x_0$ is the radial distance to the end of layer 3. This probability is shown in Figure 7-4 as a function of kaon momentum. It can be seen that in the aforementioned momentum interval the average probability for a kaon to decay before reaching layer 3 is about 13\%. This estimate
Figure 7-2  Momentum distribution of $\phi$ and its daughter kaon tracks as predicted by the Lund Monte Carlo.
Figure 7-3 Kaon reconstruction efficiency as a function of kaon a) momentum, and b) as a function of kaon transverse momentum. For kaons that do not decay the reconstruction efficiency is shown as a function of the kaon c) momentum and d) transverse momentum.
Figure 7-4 Probability that a kaon will decay before reaching the end of layer 3 at a radius of 0.53 m.
agrees well with the size of the reduction in reconstruction efficiency seen in Monte Carlo data samples.

### 7.4 Kaon Identification

Kaons are identified by using the time of flight (TOF) information only, using the standard Mark III algorithm discussed in Chapter 2 and used in the inclusive anti-proton and inclusive \( \bar{\Lambda} \) search (Chapter 5 and 6). Time of flight (TOF) information for a charged track is used if the track passes the requirements, such as polar angle cuts and quality cuts, mentioned in Chapter 2 for using the TOF system.

As previously mentioned in Chapter 2, track identification is performed by looking at the quantity

\[
wt_i = \exp \left\{ -\frac{1}{2} \frac{(t - t_i)^2}{\sigma^2} \right\}
\]

where \( t \) is the measured time, and \( t_i \) is the predicted time for the particle hypothesis \( i \) (i = e, \( \pi \), K, P). If the weight for the kaon hypothesis \( \text{wt}_K \) is larger than that for any other hypotheses, provided that \( \text{wt}_K \) is greater than a minimum value of \( 4.0 \times 10^{-6} \), then the track is identified as a definite kaon. A similar procedure is used for identifying a track as a definite pion. A track is identified as a possible kaon if \( \text{wt}_K \) is greater than \( 6.0 \times 10^{-3} \).

When reconstructing \( \phi \) mesons, at least one of the daughter kaons is required to be identified as a definite kaon. The other kaon track is allowed to be identified as a possible kaon, so long as it is not identified as a definite pion.

The efficiency for identifying an individual kaon track as a definite kaon is shown in Figure 7-5, assuming it is already reconstructed. The figure also shows the efficiencies when the kaons are not allowed to decay.
Figure 7-5 Kaon identification efficiency as a function of kaon a) momentum, and b) as a function of kaon polar angle. c) and d) shows the similar plots when kaons are not allowed to decay.
7.5 $\phi$ Reconstruction

After requiring events to pass the event selection cuts, $\phi$'s are reconstructed by combining oppositely charged kaon candidate tracks, both of which are required to pass the track selection cuts mentioned previously. As discussed in the last section, at least one of the kaon candidate tracks is required to be definitely identified as a kaon by the TOF system, where the other kaon is allowed to be identified as a possible kaon by the TOF system so long as it is not identified as a definite pion.

Once the two oppositely charged kaon tracks are identified, their invariant mass is formed. Figure 7-6 below shows this mass spectrum for both the data and the Monte Carlo at $\sqrt{s} = 3.77$ GeV. The Monte Carlo prediction is obtained by combining the results from the Lund with that of the D model Monte Carlo, which will be discussed later in this chapter. The results of the two are combined after scaling the results of each Monte Carlo to the integrated luminosity of the data at $\sqrt{s} = 3.77$ GeV.

The distribution of candidate $\phi$'s with a $K^+K^-$ invariant mass in the [1.00,1.04] GeV/c**2 range as functions of $\phi$'s momentum and the scaling variables $x_E$, $x'$, $x_B$, $\xi$ are plotted in Figure 7-7 for $\sqrt{s} = 3.77 GeV$.

7.6 Calculating the Number of $\phi$'s from $\Psi''$ Decays

To determine the number of $\Psi''$ decaying inclusively to $\phi$'s, the $\phi$ yields from radiatively produced $\Psi'$ and D meson decays as well as the yields from $\sqrt{s} = 4.14$ GeV must be subtracted from the number of $\phi$'s obtained at $\sqrt{s} = 3.77$ GeV. As discussed fully in the previous chapters the subtractions must be corrected for integrated luminosity and efficiency differences. The subtraction at $\sqrt{s} = 4.14$ GeV must also be corrected by an appropriate scale factor.
Figure 7.6 $K^+K^*$ Invariant Mass spectrum at $\sqrt{s} = 3.77$ GeV from a) data, and b) Monte Carlo.
Figure 7-7  Momentum and scaling variable distributions for candidate φ's with a $K^+K^-$ invariant mass in the [1.00,1.04] GeV/c**2 range for the data sample at $E_{CM} = 3.77$ GeV.
To be specific, the number of $\Psi'$ decaying inclusively to $\phi$'s is obtained as follows:

$$
N = \frac{N_{3.77} - N_D - \left( \frac{N_{3.77}}{N_{\text{data set}}} \right) N'}{\varepsilon_{3.77} - \varepsilon_{4.14}} - \frac{f_s (L_{3.77}/L_{4.14}) (n_{4.14})}{\varepsilon_{3.77}} (N_{\text{data set}} - n_{4.14})
$$

(EQ 7-3)

with,

- $N_{3.77}$, $n_{4.14}$, and $N'$ = Number of $\phi$'s at $\sqrt{s} = 3.77$ GeV, $\sqrt{s} = 4.14$ GeV, and at $\Psi'$ energies, respectively.

- $N_{\Psi'}^{3.77} = \text{Number of } \Psi' \text{ at } \sqrt{s} = 3.77 \text{ GeV}.$

- $N_{\text{data set}} = \text{Number of } \Psi' \text{ in } \Psi' \text{ data sample}.$

- $N_D$ is the number of $\phi$'s from $D$ decays.

- $\varepsilon_{3.77}$ and $\varepsilon_{4.14} = \text{Efficiency at } \sqrt{s} = 3.77 \text{ GeV, and } \sqrt{s} = 4.14 \text{ GeV respectively}.$

- $L_{3.77}$ and $L_{4.14} = \text{Integrated luminosity at } \sqrt{s} = 3.77 \text{ GeV, and } \sqrt{s} = 4.14 \text{ GeV respectively}.$

- $f_s = \text{Scale factor for scaling the number of events at } \sqrt{s} = 4.14 \text{ GeV to the number of events at } \sqrt{s} = 3.77 \text{ GeV}.$

It should be remembered that the number of $\phi$'s at various center of mass energies, and the efficiencies can be functions of the $\phi$ momentum and other scaling variables.

### 7.7 Overall $\phi$ Detection Efficiency

The invariant mass distribution for generated $\phi$'s from Monte Carlo is shown in Figure 7-8

The overall efficiency for detecting $\phi$'s are calculated as a function of $\phi$ momentum and various scaling variables. As an example Figure 7-9 shows the efficiency as a function of $\phi$ momentum and $x^*$ (This efficiency does not include the branching ratio of $(\phi \to K^+ K^-)$). From this figure it is seen that this analysis is sensitive to detecting $\phi$'s up to a momentum of at least 1.45 GeV/c.
Figure 7-8  Invariant mass distribution for Monte Carlo generated φ's.
Figure 7-9 Overall $\phi$ detection efficiency as function of $\phi$ a) momentum, and b) $x'$. 
7.7.1 Efficiency Ratios at the Two Center of Mass Energies

The importance of the efficiency ratios at the two center of mass energies, $\sqrt{s} = 3.77$ GeV and $\sqrt{s} = 4.14$ GeV, has already been discussed in the anti-proton chapter (Chapter 6). These ratios for $\phi$ efficiencies have also been calculated as functions of the various scaling variables. The ratios are very much consistent with 1.0 for almost all of the $\phi$ momentum spectrum. As an example Figure 7-10 shows these ratios as functions of the $\phi$ momentum and $x'$. 

7.8 Determining the Number of $\phi$'s

The number of $\phi$'s are determined by fitting the candidate $K^+K^-$ invariant mass plots with a Gaussian along with an exponential factor and a second order polynomial. This function is shown below,

$$f(m, c_i) = [1 + c_1m + c_2m] [1 - \alpha e^{-\beta(m+1)}] + \left[ \frac{c_3}{\sigma \sqrt{2\pi}} e^{-\frac{(m - m_\phi)^2}{2\sigma^2}} \right]$$

(EQ 7.4)

where $m$ is the $K^+K^-$ invariant mass, and $c_i = \{c_1, c_2, c_3, \alpha, \beta, m_\phi, \sigma\}$ are the parameters of the fit. The polynomial in the first term with coefficients $c_1$, and $c_2$ describes the background, while the Gaussian term with coefficient $c_3$, mean $m_\phi$ and width $\sigma$ describes the signal. The exponential function with parameters $\alpha$ and $\beta$ describes the abrupt rise of the invariant mass spectrum at the two kaon mass threshold $2m_K$. A typical fit is shown in Figure 7-11.

The mass spectrum is divided into bins of the chosen scaling variable. The Gaussian width $\sigma$ along with the $\phi$ mass $m_\phi$ are determined by fitting the invariant mass spectrum obtained from the Lund Monte Carlo as well as from a Lund and D model Monte Carlo combination. The latter model is formed by combining Lund and the D model Monte Carlo with appropriate weights to account for the different total cross sections of each of the models. Then the mass spectrum from the data sets are fit to this hypothesis, holding $\sigma$ and $m_\phi$ fixed at the values obtained from the Monte Carlo fits, while the coefficients of the back-
Figure 7-10  Efficiency ratios at the two center of mass energies, 3.77 GeV and 4.14 GeV, as functions of φ momentum and x'.
Figure 7-11 A typical fit of $K^+K^-$ invariant mass spectrum.
ground function are allowed to vary. The number of φ’s are then determined by obtaining the area under the Gaussian peak. The values of the width for the various x' bins are shown in Figure 7-12. The difference in the values for σ for the two methods, at each x’ bin, is included as systematic error and is shown in the figure. It is seen that σ is fairly independent of the scaling variable.

7.9 φ’s From Decays of D Mesons

Since the ψ” decays primarily to a pair of D mesons, one must subtract the contribution of D decays to the phi sample. In the two previous analyses (Chapter 5 and 6), only particle mididentification caused this particular background. In the case of φ’s, however, D mesons do decay to states containing a φ.

The Mark III D model Monte Carlo, described in Chapter 2, is used to estimate the number of φ’s. Two methods are used to arrive at this estimate. In the first method a sample of D̅D̅ events containing a φ is generated using the D model Monte Carlo. The x’ distribution of generated φ’s are plotted from this sample in Figure 7-13. It is seen that all the φ’s are in a low x’ (momentum) region where the detection efficiency is fairly low. After folding the overall detection efficiency, bin by bin, with the x’ spectrum, 38±5 events are predicted in 0.35 ≤ x’ ≤ 0.91 range.

In the second method the number of φ’s are determined by fitting the candidate K+K– invariant mass plots from a D Monte Carlo sample with the function in Equation 7-4. Using the fitting technique discussed in the previous section, 42±11 events are found with 0.35 ≤ x’ ≤ 0.91.

It is seen that the two methods compare very well with each other in determining the number of inclusive φ events.
Figure 7.12 The Gaussian widths determined from the Monte Carlo, for different $x'$ bins.
Figure 7-13 $x'$ distribution of generated $\phi$'s from the D model Monte Carlo.
7.10 Results

To determine the number of $\Psi$" decaying inclusively to $\phi$'s, the $\phi$ yields from radiatively produced $\Psi'$ and D meson decays as well as the yields from $\sqrt{s} = 4.14$ GeV must be subtracted from the number of $\phi$'s obtained at $\sqrt{s} = 3.77$ GeV. As stated Equation 7-3, the subtractions must be corrected for integrated luminosity and efficiency differences. The subtraction at $\sqrt{s} = 4.14$ GeV must also be corrected by an appropriate scale factor.

As an example, Table 7-1 displays the contributions to the number of $\phi$'s from various sources along with the average efficiencies for $\phi$ with $0.35 \leq x' \leq 0.91$. The notation is the same used in Equation 7-3.

<table>
<thead>
<tr>
<th>$N_{3.77}$</th>
<th>238±24</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{4.14}$</td>
<td>100±16</td>
</tr>
<tr>
<td>$N'$</td>
<td>164±17</td>
</tr>
<tr>
<td>$N_D$</td>
<td>42±11</td>
</tr>
<tr>
<td>$\varepsilon_{3.77}$</td>
<td>0.235±0.007</td>
</tr>
<tr>
<td>$\varepsilon_{4.14}$</td>
<td>0.242±0.006</td>
</tr>
</tbody>
</table>

It should be remembered that as in the previous analyses, the number of $\phi$'s at various center of mass energies, and the efficiencies can be functions of the $\phi$ momentum and other scaling variables.

In trying to extract the number of $\Psi$" decaying inclusively to $\phi$'s, two methods are used to scale the $\phi$ yield at $\sqrt{s} = 4.14$ GeV down to $\sqrt{s} = 3.77$ GeV, just as in the anti-proton and $\Lambda$ analyses.
7.10.1 The Scaling Variables

If scaling of the continuum production is assumed in any one of the chosen scaling variables, then the scale factor $f_s$ in Equation 7-3 becomes:

$$f_s = \frac{s_{4.14}}{s_{3.77}} = 1.21 \quad (\text{EQ 7-5})$$

where $s_{3.77}$ and $s_{4.14}$ are the square of the center of mass energies at 3.77 GeV and 4.14 GeV respectively. In this method the results are studied as functions of the appropriate scaling variable.

As an example, one scaling variable, namely $x'$, is chosen to present the methods of the analysis. At the end of this section the results of using the other scaling variables are also presented, which were obtained using similar techniques.

The number of $\Psi''$ decaying inclusively to $\phi$'s as a function of the scaling variable $x'$ is shown in Figure 7-14. The variable $x'$ is chosen only as an example. The results as functions of the other scaling variables are similar. It can be seen, from this figure, that there is no evidence for the inclusive decay of $\Psi''$ to $\phi$'s. The ratio of the number of events in the $\sqrt{s} = 3.77$ GeV data set, after correcting for the $\Psi'$ and $D$ decay contributions, to that in the $\sqrt{s} = 4.14$ GeV data set as a function of the various scaling variables, also show no evidence for $\Psi''$ decays to $\phi$'s. This result is shown for one of the scaling variables, $x'$, in Figure 7-15. These distributions of ratios have the advantage of having a very weak dependence on the values of efficiencies, since the efficiency ratios are very close to unity as discussed earlier.
Figure 7-14 Number of events after background subtractions and efficiency corrections.
Figure 7-15 Ratio of inclusive $\phi$ events at $\sqrt{s} = 3.77$ GeV and $\sqrt{s} = 4.14$ GeV, after subtracting the radiative $\Psi'$, and the $D$ decay contributions.
The net number of $\Psi''$ decaying inclusively to $\phi$'s is then determined to be $-28 \pm 174$ for $0.35 \leq x' \leq 0.91$. The results for other choices of the scaling variables are also similar and are shown in the following table.

<table>
<thead>
<tr>
<th>Scaling Variable</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_E$</td>
<td>$-29\pm181$</td>
</tr>
<tr>
<td>$x_P$</td>
<td>$-26\pm175$</td>
</tr>
<tr>
<td>$x'$</td>
<td>$-28\pm174$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$-24\pm180$</td>
</tr>
</tbody>
</table>

It should be stressed that sofar these results do not depend on any models, such as the Lund Monte Carlo. To check these results a comparison is made with the predictions of Lund, which is described in the next section.

### 7.10.2 Comparison With the Lund Monte Carlo

Since the Lund Monte Carlo is successful in predicting the correct scaling of the number of events in an exclusive channel, namely $\pi^+ \pi^- \pi^+ \pi^-$ (see Chapter 4), it is hoped, just as in the anti-proton and $\Lambda$ analyses, that it will guide us in scaling the number of $\phi$'s from $\sqrt{s} = 4.14$ GeV to $\sqrt{s} = 3.77$ GeV. At $\sqrt{s} = 3.77$ GeV, Lund predicts $339\pm13$ inclusive $\phi$ events with $0.35 < x' < 0.91$ (238$\pm24$ events are seen in the data), while $313\pm26$ events are predicted at $\sqrt{s} = 4.14$ GeV in the same $x'$ interval ($143\pm26$ events are seen in the data at this center of mass energy). The data at $\sqrt{s} = 4.14$ GeV is then scaled using the scale factor $f_s$ of Equation 7-3, where

$$f_s = \frac{n_{3.77}}{n_{4.14}} = 1.09 \pm 0.10 \quad \text{(EQ 7-6)}$$

Here $n_{3.77}$ and $n_{4.14}$ denote the number of $\phi$ events at the respective center of mass energies. Using this scale factor, one obtains $42\pm180 \Psi''$ events decaying inclusively to $\phi$'s.
7.10.3 Determining the Branching Fraction

Since \((\Psi'' \rightarrow \phi + X)\) is not observed, upper limits can be placed on the decay. However, as mentioned in previous chapters, the cross section for \(\Psi''\) production is not very well known. It is therefore more useful to place an upper limit on the product of the \(\Psi''\) cross section and the branching fraction to \(\phi\)'s. Using the results from the scaling studies the following upper limit is placed with a 90% CL:

\[
\sigma \cdot B \leq 0.035 \text{ nb}
\]

The second method of scaling, which uses Lund to predict the scale factor, places the following upper limit at 90% CL:

\[
\sigma \cdot B \leq 0.044 \text{ nb}
\]

The following table lists the upper limits on the branching ratio and on the partial widths:

<table>
<thead>
<tr>
<th>(\sigma_{\Psi''} ) (nb)</th>
<th>(\text{BR} (\Psi'' \rightarrow \phi + X) \times 10^{-3} )</th>
<th>(\Gamma (\Psi'' \rightarrow \phi + X) ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>7.0</td>
<td>165.</td>
</tr>
<tr>
<td>9.3</td>
<td>3.8</td>
<td>90.</td>
</tr>
</tbody>
</table>

of the \((\Psi'' \rightarrow \phi + X)\), using certain values for the production cross section of the \(\Psi''\).
Chapter 8

Conclusions

A search for inclusive non-$D\bar{D}$ decays of the $\Psi'(3770)$ is performed in a sample of $9.56\pm0.48$ pb$^{-1}$ collected by the Mark III detector at SPEAR. To be more specific, a search for inclusive $\bar{p}$, $\bar{X}$, and $\phi$ decay modes is performed in this data sample.

8.1 Backgrounds

Since the production of the same final state from the decay of the radiatively produced $\Psi'(3686)$ poses a potential source of background, the number of $\Psi'(3686)$ produced at the $\Psi'(3770)$ is calculated. This is done by searching for the $\Psi\pi^+\pi^-$ decay mode of the $\Psi'$. To derive the number of produced $\Psi\pi^+\pi^-$, the reconstruction efficiency for this channel is calculated by generating Monte Carlo events with a $\pi^+\pi^-$ mass distribution derived from the framework of quarkonium transitions using the Cornell potential model to describe the quark-antiquark interaction. After correcting for efficiencies and branching fractions, it is determined that $25300\pm3000$ $\Psi'$ are produced at the $\Psi'$.

Another source of background is the production of the same final state by nonresonant $e^+e^-$ annihilation. This background is subtracted by scaling the number of events observed at the higher $\sqrt{s} = 4.14$ GeV to that at the lower $\sqrt{s} = 3.77$ GeV. This is accomplished by using two techniques. In the first method the scale invariance exhibited by inclusive hadron production in $e^+e^-$ annihilation is used to scale the number of events. The LUND Monte Carlo is used in the second technique to derive the scale factor in each of the analyses. This method is shown to work for the case of exclusive $\pi^+\pi^-\pi^+\pi^-$ production.
8.2 Upper Limits Summary

A search for each of the inclusive final states mentioned above is performed. Backgrounds are subtracted and the results are corrected for detection efficiencies. After failing to observe a signal for each of the inclusive final states, upper limits are placed on the $\Psi''$ decay channels to these final states. Table 8-1 shows the calculated upper limits for each of the channels under study.

<table>
<thead>
<tr>
<th>Inclusive Channel</th>
<th>$\sigma \cdot B$ Upper Limit Using Scale Invariance (nb)</th>
<th>$\sigma \cdot B$ Upper Limit Using LUND (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}$</td>
<td>0.24</td>
<td>0.35</td>
</tr>
<tr>
<td>$\bar{\Lambda}$</td>
<td>0.058</td>
<td>0.074</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.035</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Putting the results of the three modes together, the contribution to $\sigma_{\Psi''}$ is less than 0.5 nb. Combining this with the $\sigma_{\Psi''}$ measurement by Mark III (discussed in Section 1.1), gives an upper limit to $\sigma_{\Psi''}$ of $5.5 \pm 0.5$ nb, which is still significantly less than the average $8.8 \pm 0.8$ nb obtained from the direct measurements of the $\sigma_{\Psi''}$. It should, however, be pointed out that this upper limit is now closer to the Crystal Ball result of $6.7 \pm 0.9$ nb.

The problem must lie with the direct measurements for three reasons. The first being that, the Mark III measurement of $\sigma_{\Psi''}$, which is based on the D meson branching ratio, is indirectly confirmed by CLEO, which also has measured the D meson branching ratios. The second reason is that the measurements presented in this thesis do not indicate the presence of any large non-$D\bar{D}$ decay modes of the $\Psi''$, therefore removing the suspicion of the assumption that was made in translating the D meson branching ratios into a measurement of $\sigma_{\Psi''}$. The third reason for suspecting the results of the direct measurements has to do with the inconsistencies of the results from the three experiments as seen in Table 1-1.
In light of these results, it would be a fruitful exercise to redo the direct measurement of the $\sigma_{\mu m}$. 
References


[37] Prof. J. Thaler, private communication.


Walid Abdul Majid was born on June 21, 1966 in Kabul, Afghanistan. In 1970, he entered the Tajribawi Darul-Moalimeen, graduating at the end of 1977. In 1978, he attended Habibia high school for two years. In January of 1980, after the Soviet invasion, he and his family left Afghanistan. After a brief stay in the Federal Republic of Germany, they came to the United States. He attended Swarthmore High School in Swarthmore, Pennsylvania in 1980, where he graduated in 1982. After receiving a scholarship from Swarthmore College, he graduated in 1986 with a B.A. in physics and in mathematics. He then entered the University of Illinois at Urbana-Champaign, where he received a M.S. degree in physics in 1988. Early in 1989, he started working at the Stanford Linear Accelerator Center (SLAC) with the SLD experiment. In 1991, he started an analysis of the data collected with the Mark III detector. He remained at SLAC until the middle of 1993 when he received his Ph.D. in physics from the University of Illinois at Urbana-Champaign. In August of 1993 he started working as a postdoctoral research associate at Yale University.